Acta Academica 31(3): 127-141

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An introduction to catchment runoff models with specific reference to ACRU, WASHMO and NPS

Summary

Catchment runoff models have been developed for widely differing purposes and are able to accommodate very different degrees of availability of hydrological data. The models are classified in three categories, namely as stochastic, empirical or deterministic models. This general orientation is followed by a more detailed discussion of three models: the model of the Agricultural Catchment Research Unit (ACRU), the Watershed Storm Hydrograph Multiple Options model (WASHMO) and the Non-Point Source model (NPS).

'n Inleiding tot opvangsgebied-afloopmodelle met spesifieke verwysing na ACRU, WASHMO en NPS

Afloopmodelle van opvangsgebiede is ontwikkel vir wyduiteenlopende doeleindes en is ook in staat om wye reekse van hidrologiese data te hanteer. Die modelle word in drie kategorieë geklassifiseer, naamlik stogasties, empiries en deterministies en daarna word drie modelle meer volledig bespreek: the model of the Agricultural Catchment Research Unit (ACRU), the Watershed Storm Hydrograph Multiple Options model (WASHMO) en the Non-Point Source model (NPS).

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From the detailed discussions[1] of runoff processes available in the literature and from a consideration of the complex interaction of the hydrological processes, it follows that the development of a successful runoff model, even for a small and relatively simple catchment, is a daunting task.[2] This challenge has naturally, been taken up and many runoff models now exist in the literature. However, few of these can be applied indiscriminately beyond the conditions for which they have been developed, and none of them are totally satisfactory, since most modelled runoff deviates from observed runoff (Ward & Robinson 1990: 16). These models have been developed for widely differing purposes and are able to accommodate an equally wide range of hydrological data availability, from large ungauged catchments with no rainfall data to small catchments in which many hydrological variables are monitored (Ward & Robinson 1990: 22). It is clearly not possible to review runoff modelling in a single paper. Instead the models will be classified, and then three deterministic models (ACRU, WASHMO and NPS) will be discussed to illustrate potentially promising contemporary developments. The three models have been modified and subsumed by the authors into a single ACRU-NPS-WASHMO model which has been extensively tested on the Palmiet River catchment near Durban.[3]

1. Hydrological modelling

Hydrological models can be broadly classified into three distinct categories, namely stochastic, empirical and deterministic models (Ward & Robinson 1990; Alexander 1990). *Stochastic models,* also known as probablistic models, take into consideration the chance of occurrence or probability distribution of hydrological variables such as streamflow or rainfall (Shaw 1988: 32; Ward & Robinson 1990: 28). According to Ward & Robinson (1990: 33), stochastic models

1 Gregory & Walling 1973; Shaw 1998; Ward & Robinson 1990; Miller 1996.

2 Our thanks are due to the Water Research Commission for funding the project and to all those who assisted us.

3 A full report is in preparation.

make little reference to their physical linkages with the hydrological cycle but focus strongly on the generation of synthetic runoff series to accommodate the variations in runoff over time. They therefore represent the relevant statistical properties.

According to Ward & Robinson (1990: 36), most of the stochastic models attempt to accommodate three main assumptions in generating these synthetic runoff series, namely:

- that the recorded historical sequence as a subset of the stream flow record is extremely unlikely to recur;
- that it is unlikely that the maximum possible flood for a given stream is included within the historical record, meaning that there is always a possibility that the highest recorded flood will be superseded by an extreme event in the future, and
- that the stream flow exhibits persistence, meaning it will show groupings of wet and dry years reflected in the levels of stream flow.

An example of stochastic modelling is to be found in the autoregressive integrated moving average (ARIMA) models (Ward & Robinson 1990: 38). The Thomas-Fiering model (as discussed in Shaw 1988: 12) is another example of a stochastic model in the form of regression analyses which are used to create monthly flow data. Both these models combine any significant serial correlation properties of a data series with the smoothing effects of an updated running mean throughout the series (Shaw 1988: 14).

In the final analysis, however, the potential of stochastic modelling techniques will only be fully developed when stochastic runoff models incorporate an adequate physical conception of the catchment from which the runoff derives. Until that has been achieved of Klemes' (1978: 286) warning that "enquiry into the stochastic aspects of hydrology provides no prerogative for ignoring hydrology itself" must be heeded.

Empirical models of flood series, described in Alexander (1990), are based on maximum recorded floods on a world-wide basis. According to Ward & Robinson (1990: 116) the distinction between empirical and deterministic models lies in the degree of consideration given to the physical processes which act on the input variables to produce runoff from a catchment. The two empirical models most often used in South Africa are based on the Creager method and the regional maximum flood method (Schmitz *et al* 1993). The Creager method is based on a historical analysis of the maximum floods experienced in catchments similar in size to the catchment under consideration (Alexander 1990: 66). The regional maximum flood method was developed by Kovacs in the 1980s and is based on the Francou and Rodier method developed in the 1960s (Alexander 1990: 72). The catchment coefficient (represented as K-values) used in the regional maximum flood method by Kovacs in 1988 were revised in light of the 1984 Domoina floods (Alexander 1990: 74).

The third category of hydrological models comprises the *deterministic hydrological models*. These models simulate some of the physical processes operating in the catchment and converting rainfall and other precipitation forms into runoff (Schmidt & Schulze 1987). Catchment characteristics such as catchment slope, channel gradient, soil types, infiltration processes, land cover and antecedent soil moisture all have an influence on the amount of runoff available as well as on the shape of the flood hydrograph (Ward & Robinson 1990; Alexander 1990).

According to Alexander (1990: 81) the rainfall-runoff models derive their structure mainly from modules which determine the catchment response time, the corresponding rainfall intensity distribution and the proportion of the rainfall contributing directly to runoff from the catchment (determined by catchment characteristics such as soil type and antecedent soil moisture conditions). Kinematic models, which are based on the kinematic theory of flow, are therefore classified as deterministic models (Kuo *et al* 1996), as are ACRU and WASHMO which are discussed below.

Deterministic models, according to Alexander (1990: 84), must meet several requirements: they must provide accurate estimates in terms of runoff; their results must be consistent (ie when a model is applied to similar problems the results must be similar); they must be applicable to a variety of situations; they must not produce questionable results in extreme situations, and they must be generally accepted and widely used in practice.

According to Shaw (1988: 44) water quality in streams, rivers and lakes has three main features, namely physical, chemical and biological. Solids or physical features range from minute particles to tree trunks and boulders, depending on the discharge and flow velocity. The colour, taste and odour of the water, as well as its turbidity and temperature, also classify as part of the physical features of water quality. Chemical features of water quality include dissolved oxygen, biochemical oxygen demand, nitrogen, phosphorus, heavy metals and chlorides. Parasites such as *Schistosoma* and bacteria such as *Echerichia coli* are examples of biological features of water quality.

Due to the shortage of data relating to water quality, hydrologists make use of mathematical modelling techniques to generate information. These models are based on analytical solutions derived from well researched catchments and transferred to catchments where little or no data is available (Johanson *et al* 1994). Some models simulate the complex physical, chemical and biological processes in rivers (Shaw 1988), while others are used to assess the impact of different actions and decisions relating to river basin management (Ward & Robinson 1990).

2. The ACRU model

The ACRU model was originally developed in the 1980s as an agrohydrological model by the Agricultural Catchments Research Unit situated in the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg. The need for an agrohydrological model for Southern African conditions became clear from research done by Schulze in 1983 on an agrohydrological and agroclimatological atlas for the then Natal (Schulze *et al* 1995). The ACRU model is a physical-conceptual, multipurpose model embracing the processes in a catchment and outputting these into runoff elements, reservoir yields, demand and supply of irrigation water, the effect of changes in land use and so on (Schulze *et al* 1995).

The ACRU model was developed essentially to operate on catchments where urban areas comprised 20% or less. Since then the model has been adapted to incorporate catchments whose urban areas exceed 20%. This was attempted in a project funded by the Water Research Commission and conducted on the Mgeni Catchment by Tarboton and Schulze in 1992 (Tarboton & Schulze 1992). According to Schulze *et al* (1995: 104) typical applications of the ACRU model are flood estimation, demand and supply of irrigation water, crop yield and primary production modelling. The ACRU model has also been used to study water resources: the impact of changes in land use on water resources; the hydrological impact of wetlands; the potential effect of global warming on crop production and hydrological responses (Schulze *et al* 1995).

ACRU is designed to operate as a point or lumped catchment model with ideal catchment sizes in the lumped mode not exceeding 30 km^2. In the lumped version ACRU cascades from one catchment to the next. Output from each sub-catchment can be obtained if the user wishes. Inputs to each of the sub-catchments can vary to suit different simulations and outputs. To simulate changes over time the ACRU model makes provision for the use of dynamic input options to cater for the desired changes, whether to land use, land cover, or any other variable. Both abrupt and gradual changes can be modelled (Schulze *et al* 1995).

Data is keyed into ACRU via the ACRU Menubuilder, which incorporates a Decision Support System to assist the user in inputting data. To aid the user further, the ACRU Input Utilities were developed to help the user to prepare the data and information needed for a simulation run. The ACRU 3.00 Version also makes use of an Outputbuilder for the selection of variables that the user needs in the output and further analysis. This is done in conjunction with the ACRU Output Utilities (Schulze *et al* 1995).

3. The WASHMO model

According to Middleton *et al* (1984: 12) the WASHMO[4] model was developed at the Agricultural Engineering Department at the University of Kentucky. The model is a modified version of the original

4 Acronym for Watershed Storm Hydrograph Multiple Options.

WASH model which then consisted solely of Haan's unit hydrograph (Ward *et al* 1979). The WASHMO model is based on the US Department of Agriculture's Soil Conservation Service (SCS) procedures for small watersheds. The surface runoff is determined by the SCS Curve Number method (Middleton *et al* 1984). It is suitable for linkage with ACRU since that model's peakflow simulation is also based on SCS procedures (Schulze 1989; Smithets & Schulze 1995).

The *Curve Number* in the SCS, WASHMO and ACRU models is an indicator of the runoff potential of an area and varies with soil type, land use and soil moistute conditions. For the theory and development of the curve numbers and their applications under South African conditions the reader is referred to the work of Schmidt and Schulze (1987).

In WASHMO the rainfall intensity is incorporated into the model by means of the selection of various synthetic rainfall distributions, namely *SCS Type I, SCS Type II* and the input of the user's own actual rainfall distribution (Middleton *et al* 1984). For the project under discussion, a further four synthetic rainfall intensity distributions were added to take South African regional conditions into account. These four distributions are shown in Figure 1. If the duration of the storm is less than 24 hours, WASHMO determines the synthetic rainfall distribution by selecting the various ratios needed for the shorter storm. WASHMO has been developed to use unit hydrograph procedures. It offers the user a choice of three approaches, namely Haan's unit hydrograph for urban areas; the Double Triangle hydrograph for rural areas, agriculture and so on, and the use of user-defined inputs.

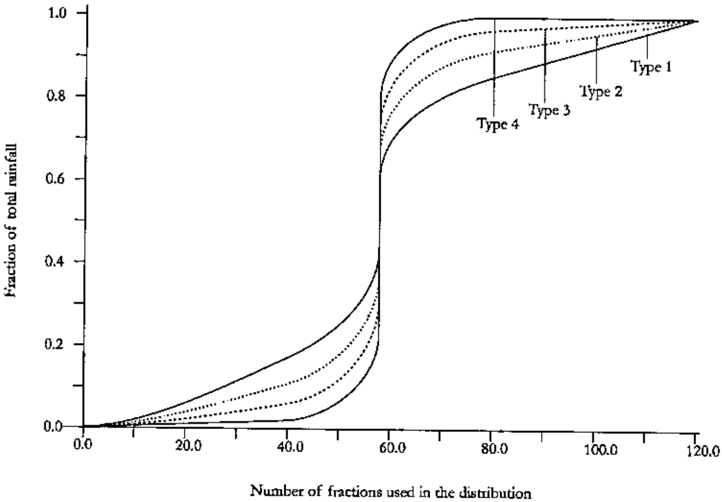

Figure 1: The four different synthetic rainfall distributions as used in the WASHMO model adapted from Wedepohl (1988)

Urban areas consist of paved and unpaved areas which affect runoff in different ways. The original SCS model made provision for impervious areas by using Curve Numbers (Schulze & Arnold 1979) but it does not make provision for a distinction between connected and unconnected impervious surfaces. This was addressed by the SCS's release of Technical Report No 55 in 1986 (US Dept of Agriculture 1986). This concept is also used by Tarboton & Schulze (1992) for the Mgeni catchment project.

Since the WASHMO model is based on the SCS procedures the concept has been incorporated into WASHMO by the present authors.

WASHMO was designed with the option of user-defined rainfall distribution input, but the WASHMO model could only accept a three-minute rainfall interval for its own rainfall distribution (Tapp 1981). In ACRU, WASHMO was consequently developed to accept any rainfall time interval.

A catchment is divided into pervious and impervious surfaces and the impervious surfaces are then further sub-divided into connected (adjimp) and unconnected (disimp) impervious surfaces. The total area of the catchment or sub-catchment (100%) is then divided into percentages of pervious, connected impervious and unconnected impervious surfaces. The division of the impervious areas into connected and unconnected surfaces is based on the same principle as in Tarboton & Schulze (1992: 32).

The WASHMO model was developed as a single-event storm hydrograph model. Design storms of a certain return period are used in areas where no runoff records are available for the construction of structures or the delimitation of floodlines. For design purposes, rainfall with certain return periods is used to produce a flood event of the same return period. With the incorporation of the WASHMO model into ACRU, the ACRU model was altered so as to act as a single event storm hydrograph model if required.

4. The water quality model (ACRU-NPS)

There are two approaches to water quality modelling, namely a statistical and a deterministic approach. The non-point source model linked to ACRU is a deterministic water quality model. The aim of the development of the NPS model was to provide a model which simulates urban impact on water quality and is easy to use (Schmitz *et al* 1993).

The sources of non-point pollution include atmospheric deposition, agricultural activities, and runoff from developing or fully urbanised areas (Todd *et al* 1989). Baan & Berbee (1989) report on a study conducted in the Netherlands which showed that, in spite of strict legislation concerning point pollution, water quality did not improve to the expected levels. It was discovered that non-point sources do have a significant impact on water quality. For this reason it was decided to use a non-point source model (ACRU-NPS) as a water quality model in ACRU.

5. Accumulation and washoff of pollutants

Several models, such as the *NPS* model (Donigian & Crawford 1976), the *HSPF* model (Johanson *et al* 1984), the *BMPSOFT* model (Kuo *et al* 1988) and the *SWMM* model (Wanielista 1979, as referenced in Kuo *et al* 1988), use the principle of mass accumulation on the catchment surface during dry periods. On wet days a fraction of the mass is washed away from the surface by runoff. The fraction of the mass washed off is directly proportional to the amount of runoff. In ACRU-NPS, as in the HSPF model (Johanson *et al* 1984), the washoff is determined from pervious and impervious areas and the total washoff load is achieved by weighting each value by the percentage of pervious and impervious areas in the catchment (Schmitz *et al* 1993). Washoff from the various surfaces is treated separately and then combined to give a single output value as a concentration in mg/l or as an export value in kg/interval. Separate routines also exist assessing for the accumulation of pollutants, the unit removal rate of pollutants, the pollutant build-up rate and the deposition originating from motor vehicles.

For the daily time step section of the ACRU-NPS model the equation has been changed in such a way that the time increment is omitted to facilitate full washoff if the rainfall is sufficient.

6. Contribution of atmospheric fallout to pollutant loads

In his research on Pinetown from 1982 to 1985, Simpson (1986) estimated the contribution of atmospheric fallout to runoff loads by comparing the mean concentrations for bulk fallout with runoff loads. These estimates are given as the percentage of atmospheric fallout contribution to the runoff loads (Simpson 1986: 52).

This percentage is included as an input variable in the non-point source model in ACRU to ascertain the catchment's own input to the pollution loads. After the washoff loads from both surfaces have been estimated, the pollution load from the atmospheric fallout is corrected in the mass balance by the percentage contribution to the runoff load using the following equation:

Pload = Wtot/(C%/100.0)

where

Pload = the runoff from the catchment including atmospheric fallout contributions (kg/ha per day)

Wtot = total washoff from both surfaces (kg/ha per day)

C% = percentage contribution of atmospheric fallout to runoff loads.

7. Linkage to the ACRU model

For both the WASHMO and the non-point source model, subroutines were written by the present authors for the ACRU model. The input values needed to run these subroutines were added to the MENU which ACRU uses to read in input values. Further subroutines were written to facilitate output from these subroutines. The subroutines are called up from the ACRU main program. Figure 2 shows the ACRU main program with ACRU-NPS-WASHMO linked to the section for runoff components.

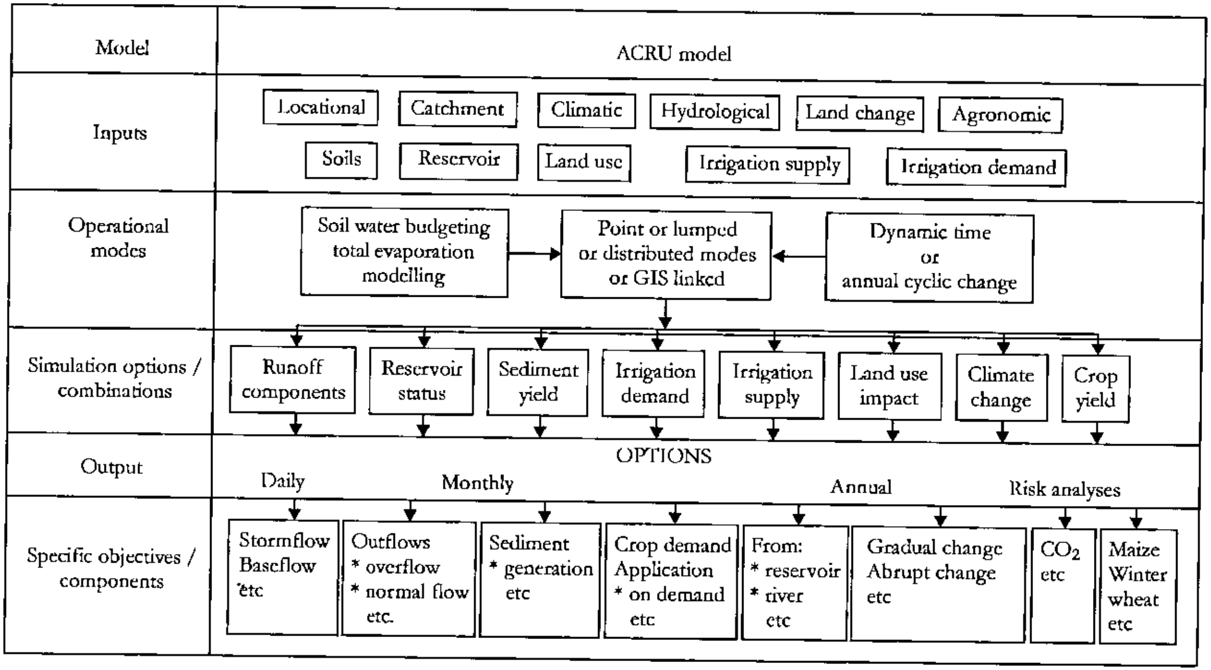

Figure 2: The ACRU model (Smithers & Schulze 1995: 22) with NPS-WASHMO as a simulation listed option under runoff components

8. Conclusion

In the introduction it was indicated that a totally satisfactory model (one which always simulates absolutely correctly) does not exist. In spite of this, models have been vastly improved over the last few decades and very good results can be obtained from many models. However, the quality of the output depends heavily on the quality of the input (which implies meticulous data gathering) and the model selected should be site specific. The nature of the catchment (ie size, land-use, etc) will also play a role in model selection.

The ACRU-NPS-WASHMO combination which resulted from this research offers an opportunity for testing under real flow conditions. This was extensively implemented in the Palmiet River near Durban. A report is being prepared which will discuss the procedures and results.

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