Journal of Hydrology, 147 (1993) 1–36

0022-1694/93/$06.00 © 1993 – Elsevier Science Publishers B.V. All rights reserved

[4]

Comparison of six rainfall–runoff modelling approaches

F.H.S. Chiew*, M.J. Stewardson, T.A. McMahon

Centre for Environmental Applied Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Vic. 3052, Australia

(Received 17 November 1992; revision accepted 6 January 1993)

Abstract

Six rainfall–runoff modelling approaches — simple polynomial equation, simple process equation (tanh equation), simple time-series equation (Tsykin equation), complex time-series model (IHACRES), simple conceptual model (SFB) and complex conceptual model (MODHYDROLOG) — are compared in this paper with the models used to simulate daily, monthly and annual flows in eight unregulated catchments. The complex conceptual model gives, by far, the best simulation of daily high and low flows, and can estimate adequately daily flows for the wetter catchments. It can provide satisfactory estimates of monthly and annual catchment yields in almost all catchments. However, the time-series approaches and the simple conceptual model can also provide adequate estimates of monthly and annual yields in the wetter catchments. As it is much easier to use these approaches than the complex conceptual model, the simpler methods may be used to estimate monthly and annual runoff in the wetter catchments.

Introduction

Methods used to estimate runoff from rainfall (and evapotranspiration) are frequently classified into two groups — 'black box' models and process models. In the 'black box' modelling approach, empirical equations are used to relate runoff and rainfall, and only the input (rainfall) and output (runoff) have physical meanings. Simple mathematical equations and time-series methods fall into this category. Process models attempt to simulate the hydrological processes in a catchment and involve the use of many partial differential equations governing various physical processes and equations of continuity for surface and soil water flow. Examples include the approach set out by Freeze and Harlan (1969), the Institute of Hydrology (UK) Distributed

---

* Corresponding author.

Model (IHDM) (see Beven et al., 1987) and the Système Hydrologique Européen (SHE) model (see Abbott et al., 1986a,b). However, 'process' models require the use of many parameters, and data limitations and the difficulty in relating theoretical equations that describe hydrological processes on small laboratory scales to spatially heterogeneous and time-varying systems in a catchment may not justify the use of these models to estimate runoff (see also Beven, 1989). A simpler approach is to conceptualise a catchment as a number of interconnected storages, with mathematical functions to describe the movement of water into, between, and out of them. Conceptual rainfall-runoff models can thus be considered as a third group of modelling approach. They attempt to represent the catchment physical processes but often include 'black box' treatment where empirical equations and 'effective' parameters are used to describe the processes.

It is common to find models applied or independently tested by users not associated with the model development, but it is rare to find any systematic application and comparison of models on the same catchment. The World Meteorological Organization (1975) conducted a study in which the performance of 10 rainfall–runoff models was compared. Although six catchments were selected for that study (the catchments were relatively large, the smallest being 1445 km^2 and the largest 131 500 km^2), only two models were applied to all six catchments. In addition, the data for some of the catchments were 'thought' to be inadequate (see also Sittner, 1976). As such, limited conclusions were drawn from that study. Moore and Mein (1975) and Weeks and Hebbert (1980) also carried out model comparison studies. However, their studies were limited to the comparisons of complex conceptual rainfall–runoff models (and one time-series equation in the case of Weeks and Hebbert). Moore and Mein (1975) applied three models to four catchments in south-eastern Australia, and Weeks and Hebbert (1980) applied five models to three catchments within one geographic region in the south-west of Western Australia.

This paper describes the comparison of six rainfall–runoff modelling approaches (simple polynomial equation, simple process equation, simple time-series equation, complex time-series model, simple conceptual model and complex conceptual model). The models are applied to eight catchments throughout Australia, which have different physical and climatic characteristics. The model complexities and the computing times required for successful optimisation of model parameters are discussed and the streamflow volumes estimated by the six approaches are compared with the recorded streamflow volumes to investigate the following issues: (1) relative performance of the modelling approaches in simulating runoff over different time periods (daily, monthly and annual); (2) quality of model estimates of catchment streamflow yields for low flows; (3) whether there is sufficient representation of the surface hydrology to allow the model to predict runoff for an independent test period; (4) whether certain approaches are more suited to catchments with particular characteristics.

Description of modelling approaches

Simple polynomial equation

A simple polynomial equation is used to relate streamflow to rainfall:

$$\text{RUN} = a + b\,\text{RAIN} + c\,\text{RAIN}^2 + d\,\text{RAIN}^3 + e\,\text{RAIN}^4 + \ldots \tag{1}$$

where RUN and RAIN are runoff (mm) and rainfall (mm), respectively, over the same time period and a, b, c, d, e, ... are parameters.

Simple process equation (tanh equation)

The tanh equation, which follows Boughton (1968), is used:

$$\text{RUN} = \text{RAIN} - a - b\tanh\left(\frac{\text{RAIN} - a}{b}\right) \tag{2}$$

where a and b are parameters. Unlike the simple regression equation, Eq. (2) attempts to provide a simple description of the catchment physical processes. a represents the maximum value of precipitation below which runoff would not occur (e.g. rainfall must exceed canopy interception and saturate the soil before runoff can occur) and b, is a rate factor controlling additional precipitation losses through the exponential tanh function ($b = 0$, no additional losses; $b = \infty$, total loss). The tanh equation has been used by McMahon et al. (1992) to estimate annual runoff, and by Gan et al. (1990) and Chiew and McMahon (1993a) to infill missing annual streamflow records.

Expressions similar to Eq. (2) are also used in two conceptual rainfall–runoff models (the Boughton model (1968) and the SFB model (Boughton, 1984)) to simulate surface runoff. The tanh equation also has the well-known form of the US Soil Conservation Service curve number (US Soil Conservation Service, 1972) and follows closely Budyko's (1977) curve reproduced by Nemec and Rodier (1979).

Simple time-series equation (Tsykin equation)

In the time-series equations, runoff is related not only to rainfall in the current time period, but also to rainfall in previous periods. The time-series equations can take various forms, and, for the purpose of this study, a simple equation based on multiplying components proposed by Tsykin (1985) is used:

$$\mathrm{RUN}_i = a + b\,\mathrm{RAIN}_i^c\,\mathrm{RAIN}_{i-1}^d\,\mathrm{RAIN}_{i-2}^e\,\mathrm{RAIN}_{i-3}^f \ldots \tag{3}$$

where RUN_i is runoff in the time period i, RAIN_i is rainfall in the time period i, RAIN_{i-1}, $\mathrm{RAIN}_{i-2}, \ldots$ are rainfalls in the periods $i-1$, $i-2, \ldots$ respectively, and a, b and $c, \ldots$ are empirical parameters. Tsykin (1985) reported that Eq. (3) gives better estimates of runoff than time-series equations of other forms (e.g. summation of components). We also found that Eq. (3) gives better estimates of runoff than the summation of time-series components. Equation (3) has been used by Tsykin (1985) to obtain satisfactory estimates of daily runoff on various catchments throughout Australia, particularly in Western Australia.

Complex daily time-series model (IHACRES)

The complex time-series model has a series of empirical equations relating runoff to the rainfall time series. An approach based on the IHACRES model (jointly developed by the Institute of Hydrology of the UK and the Centre for Resource and Environmental Studies in the Australian National University, and described by Jakeman et al. (1990) and Jakeman and Hornberger (1993) is used for this study.

Rainfall excess is obtained from the rainfall in each time period by a nonlinear relationship

$$\mathrm{EX}_i = z\,\mathrm{RAIN}_i\,\mathrm{STORE}_i \tag{4}$$

where EX is rainfall excess, z is a factor required to ensure the equivalence in volumes of rainfall excess and total recorded streamflow over the modelling period and STORE is a catchment wetness index. The index, STORE, is calculated as a weighting of the rainfall time series, the weights decaying exponentially backwards in time:

$$\mathrm{STORE}_i = \mathrm{RAIN}_i + (1 - \tau_i^{-1})\,\mathrm{STORE}_{i-1} \tag{5}$$

The rate at which the catchment wetness declines, τ_i, is dependent on the temperature and the storage on the previous day:

$$\tau_i = \tau \exp f(20 - \mathrm{TEM}_i) \exp(-p\,\mathrm{STORE}_{i-1}) \tag{6}$$

where TEM is temperature and τ, f and p are model parameters.

Runoff is related to rainfall excess by a linear recursive equation,

$$\mathrm{RUN}_i = -a_1\ \mathrm{RUN}_{i-1} - a_2\ \mathrm{RUN}_{i-2} + b_0\ \mathrm{EX}_i + b_1\ \mathrm{EX}_{i-1} \tag{7}$$

where a_1, a_2, b_0 and b_1 are model parameters.

There are therefore seven parameters (a_1, a_2, b_0, b_1, τ, f and p) in the IHACRES model in the form used for this study. The use of four parameters in Eq. (7) describes a two-component linear model (in parallel) defining a 'quickflow' and a 'slowflow' response. IHACRES has been successfully applied to various catchments throughout the world, as described by Jakeman and Hornberger 1993 and in the references of that paper.

Simple conceptual daily rainfall–runoff model (SFB)

The SFB model (Boughton, 1984), which was developed primarily for estimating water yield in ungauged catchments, is used for this study. Its three parameters, surface storage capacity (S), daily infiltration capacity (F) and baseflow factor (B), are purported to be related to physical catchment characteristics (relationships given by Boughton (1984)). The SFB model uses daily rainfall and potential evapotranspiration as input data. A

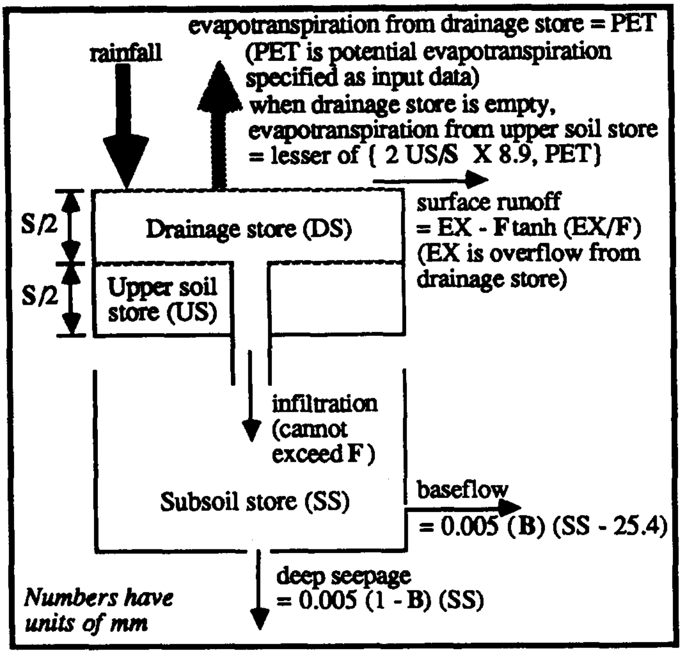


Fig. 1. Schematic representation of the SFB daily rainfall-runoff model.

schematic diagram of the model structure, with equations describing water movement, is given in Fig. 1.

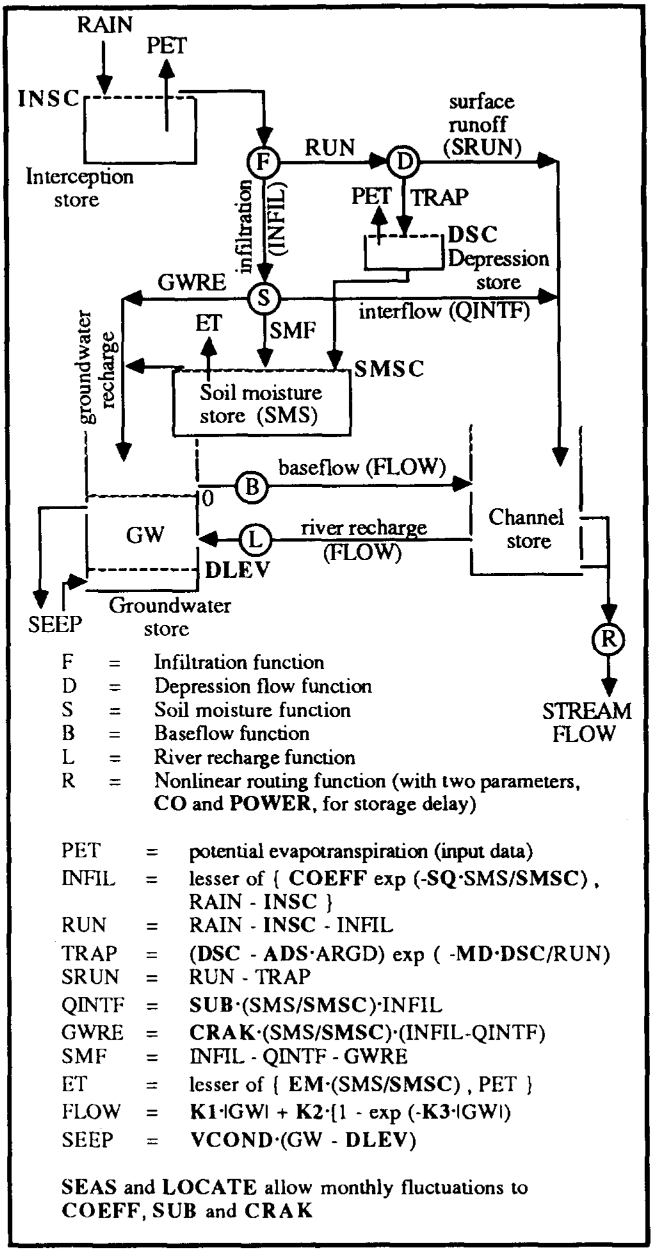
In the SFB model, daily rainfall first fills the upper soil store, and any excess water enters the drainage store. Surface runoff occurs when the drainage store is full. Water from the drainage store infiltrates into the subsoil store at a maximum daily rate of F. Evaporation from the drainage store occurs at the potential rate. When the drainage store is empty, evapotranspiration from the upper soil store occurs at a rate proportional to the soil moisture status (but must not exceed the potential rate). The subsoil store is depleted by deep seepage (which occurs every day) and baseflow (which occurs when the water level in the subsoil store exceeds 25.4 mm). The model makes no attempt to simulate the time sequencing of runoff, and the total runoff is given by the sum of the surface runoff and baseflow.

Other models which fall into this category of 'simple conceptual rainfall–runoff models' include the four-parameter models developed by Haan (1972) and by Sukvanachaikul and Laurenson (1983) and the two-parameter MOSAZ Model developed by Jayasuriya (1991). Although these models serve as simple prediction devices for estimating runoff from rainfall, they do not truly represent the movement of water in the catchment. For example, what is termed 'infiltration' in the models may in fact be a combination of 'true' infiltration, interception and surface storage (Haan, 1972).

Complex conceptual daily rainfall–runoff model (MODHYDROLOG)

The daily rainfall–runoff model, MODHYDROLOG (Chiew and McMahon, 1991), is used for this study. MODHYDROLOG is the modified version of HYDROLOG (Porter and McMahon, 1976), with improved representation of the groundwater processes. The model attempts to include as many component parts as are necessary to simulate the hydrological processes and which can be described adequately in simple mathematical terms of physical significance. The model structure and the equations representing the various hydrological processes are shown in Fig. 2. MODHYDROLOG has 19 parameters, and they are highlighted in bold in Fig. 2.

In MODHYDROLOG, incident daily rainfall first fills the interception store, which is emptied each day by evaporation. The excess rainfall is then subjected to an infiltration function which determines the amount of water that infiltrates into the soil. Some of the water than cannot infiltrate is diverted to the depression store, as regulated by the depression flow function, and the remainder (surface runoff) flows to the stream. The soil moisture function proportions the infiltrated water as interflow into the stream, recharge into the groundwater store and water into the soil moisture store. Evapotranspiration



F = Infiltration function
D = Depression flow function
S = Soil moisture function
B = Baseflow function
L = River recharge function
R = Nonlinear routing function (with two parameters, **CO** and **POWER**, for storage delay)

PET = potential evapotranspiration (input data)
INFIL = lesser of { **COEFF** exp (-**SQ**·SMS/SMSC), RAIN - **INSC** }
RUN = RAIN - **INSC** - INFIL
TRAP = (**DSC** - **ADS**·ARGD) exp (-**MD**·**DSC**/RUN)
SRUN = RUN - TRAP
QINTF = **SUB**·(SMS/**SMSC**)·INFIL
GWRE = **CRAK**·(SMS/**SMSC**)·(INFIL-QINTF)
SMF = INFIL - QINTF - GWRE
ET = lesser of { **EM**·(SMS/**SMSC**), PET }
FLOW = **K1**·|GW| + **K2**·[1 - exp (-**K3**·|GW|)
SEEP = **VCOND**·(GW - **DLEV**)

SEAS and **LOCATE** allow monthly fluctuations to **COEFF**, **SUB** and **CRAK**

Fig. 2. Schematic representation of the MODHYDROLOG daily rainfall–runoff model.

from the soil moisture store occurs at a rate which is dependent on the soil moisture status (similar to the SFB model). The soil moisture store has a finite capacity and overflows into the groundwater store. The groundwater store can be depleted by baseflow into the stream and by deep seepage to the underlying aquifers, or replenished by recharge from the stream and by upward movement of water from the underlying aquifers. In MODHYDROLOG, water in the channel store (from surface runoff, interflow and baseflow) is routed to the catchment outlet using a nonlinear routing technique.

MODHYDROLOG is purported to be 'physically based', and Chiew and McMahon (1993b) showed that certain model parameters can be related to the catchment characteristics. However, it is difficult to estimate the values of some of the important parameters and MODHYDROLOG should be calibrated against streamflow data in all applications. HYDROLOG and MODHYDROLOG have been applied extensively throughout Australia (see Chiew and McMahon (1993b) and references therein). Other models which fall into this category of 'complex conceptual rainfall–runoff models' include the 16-parameter Sacramento model (Burnash et al., 1973), the 17-parameter Stanform model (Crawford and Linsley, 1966) and the 13-parameter Boughton model (McMahon and Mein, 1973).

Description of catchments

The six modelling approaches are applied to eight unregulated catchments listed in Table 1. These catchments are selected from the 'benchmark' catchments identified by the Australian Bureau of Meteorology (1991), with the assistance of State and Territory Water Agencies, as part of a project on 'Monitoring Climate Change and its Impact on Australia's Water Resources' endorsed by the Australian Water Resources Council. The eight catchments represent a wide range of climatic and physical characteristics throughout Australia. Records for these catchments are generally good, with two to four rainfall stations used to represent the average catchment rainfall (using a Theissen weighting), and daily potential evapotranspiration calculated from Morton's procedure (1983) using climate data from stations close to the catchments. The preparation of the complete sets of daily rainfall, climate, potential evapotranspiration and streamflow data has been described by Chiew and McMahon (1993c). The plots in Figs. 3 and 4 show monthly and annual rainfall and streamflow hydrographs, respectively, for the eight catchments.

Alligator Creek at Allendale has a catchment area of 69 km^2 and is located in the Ross River Basin in the central coast of Queensland. The mean annual

Table 1
Locations, periods of record and some climatic characteristics of the eight catchments used for this study

Catchment	Period of record use for study	Location of streamflow station at catchment	Catchment area (km^2)	Mean annual runoff (ML) (mm)	Mean annual rainfall (mm) (season)
118106 Alligator Creek at Allendale	1975–1989	19°23′S, 146°57′E	69	33 000 (480)	1100 (summer)
215004 Corang River at Hockeys	1980–1989	35°09′S, 150°02′E	166	55 000 (330)	800 (uniform)
238208 Jimmy Creek at Jimmy Creek	1970–1989	37°23′S, 142°21′E	23	3700 (160)	650 (uniform)
307001 Davey River downstream of Crossing River	1974–1990	43°09′S, 145°56′E	686	1 390 000 (2000)	2100 (winter)
403218 Dandongadale River at Matong North	1974–1984	36°48′S, 146°38′E	182	70 000 (380)	1300 (winter)
509503 Kanyaka Creek at Old Kanyaka	1978–1989	32°10′S, 138°17′E	180	330 (2)	300 (winter)
616065 Canning River at Glen Eagle	1977–1987	32°14′S, 116°10′E	544	8700 (20)	800 (winter)
915001 Mitchell Grass at Richmond	1976–1988	20°45′S, 143°08′E	3	50 (15)	450 (summer)

	Average daily maximum temperature (°C)		% time when daily streamflow is		% time when monthly streamflow is zero
	Winter	Summer	< 1 ML	zero	
118106	25	32	27	24	15
215004	12	26	4	4	0
238208	12	26	< 1	< 1	0
307001	9	19	0	0	0
403218	10	25	< 1	< 1	0
509503	16	34	99	43	30
616065	16	31	54	49	39
915001	26	37	> 99	> 99	94

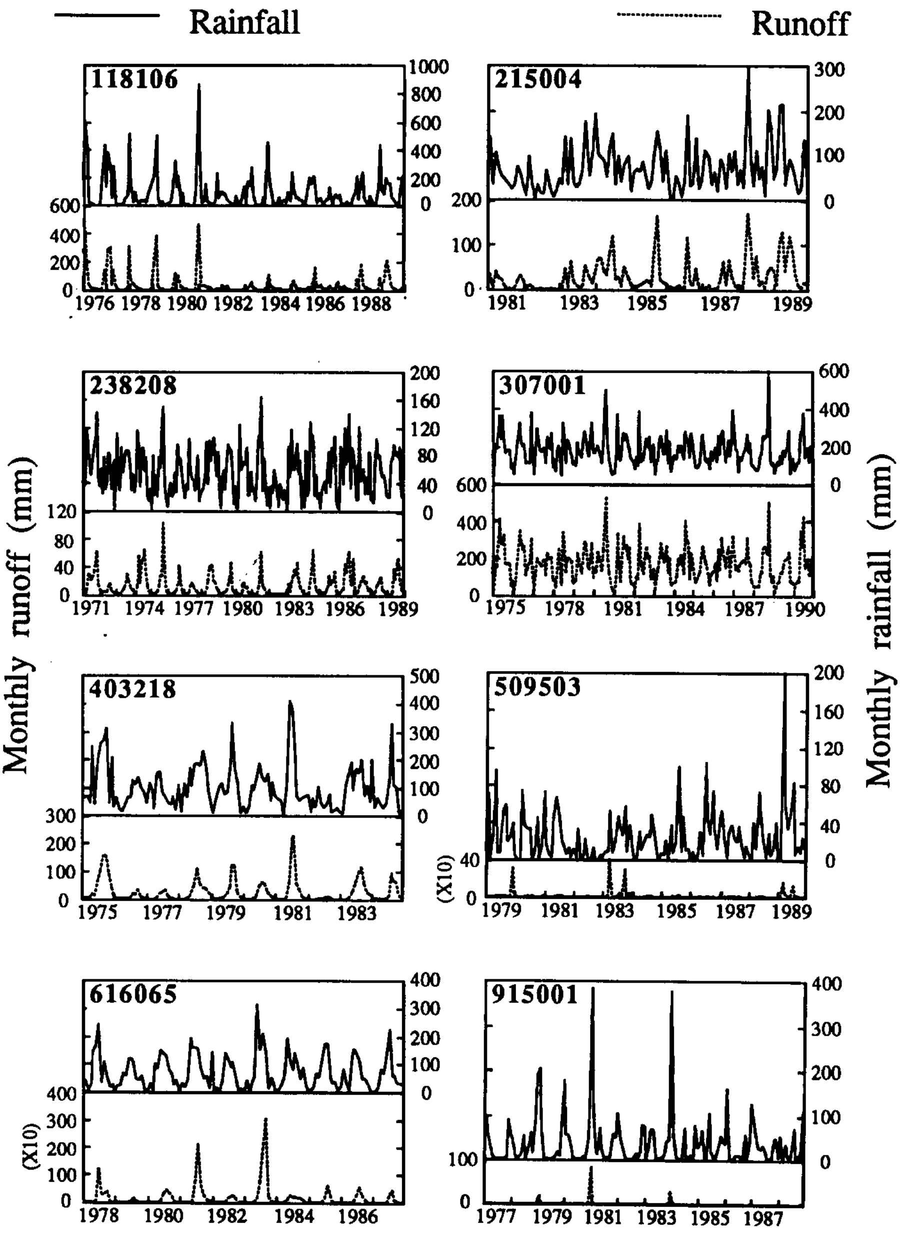


Fig. 3. Monthly rainfall and streamflow in the eight unregulated catchments used for this study.

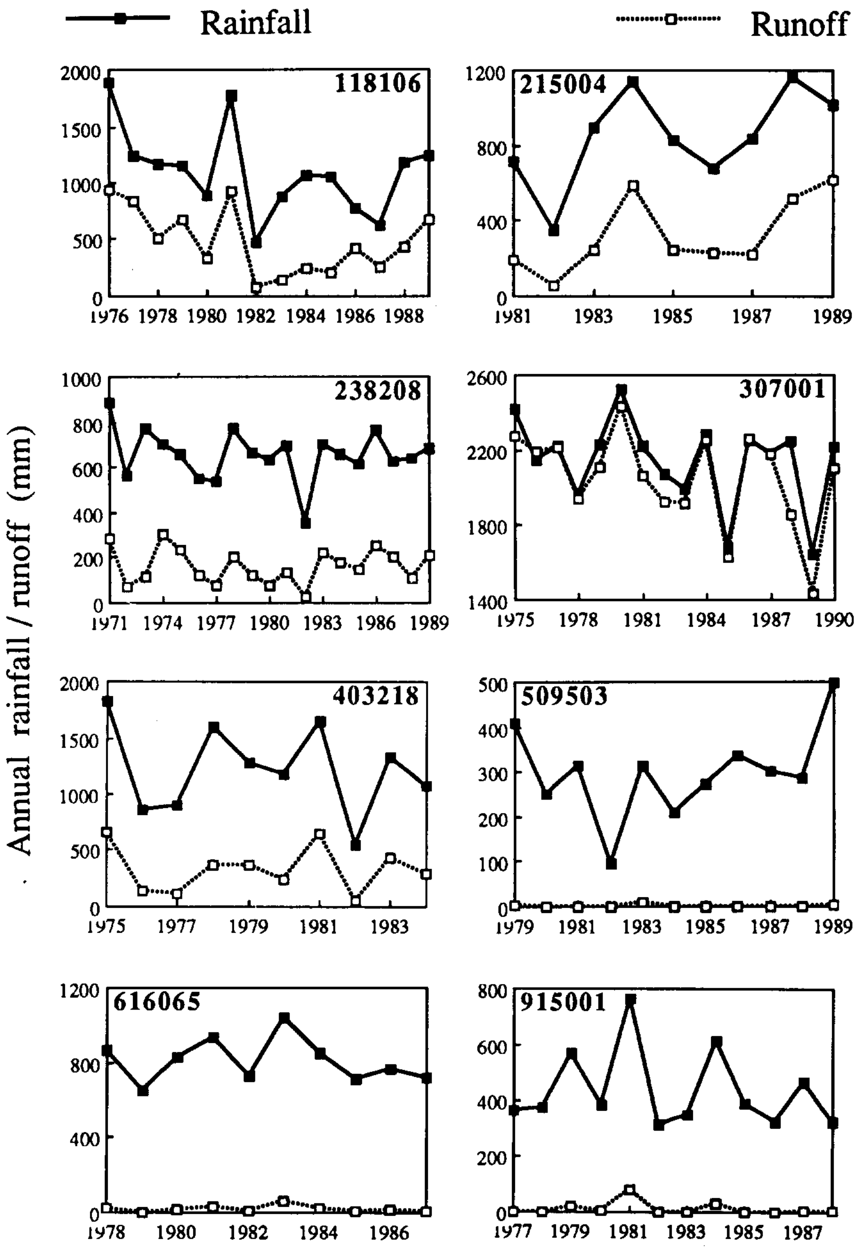


Fig. 4. Annual rainfall and streamflow in the eight unregulated catchments used for this study.

runoff is 33 000 ML (480 mm) (1 ML = 1000 m^3). It has a tropical climate, with average maximum daily temperatures ranging from 25°C in winter to 32°C in summer and a mean annual rainfall of 1100 mm, 60% of which falls during the three summer months (December–February). The catchment has fairly steep slopes (10–1200 m AHD (Australian height datum)) and is covered predominantly by medium-height (10–30 m) eucalyptus trees (30–70% foliage cover). The soil type is predominantly red friable earths with massive and porous sandy clay subsoils.

Corang River at Hockeys has a catchment area of 166 km^2 and is located in the Shoalhaven River Basin in the central coast of New South Wales. It has a temperate climate, with an average daily maximum winter temperature of 12°C and an average daily maximum summer temperature of 26°C. The mean annual runoff is 55 000 ML (330 mm) and the annual rainfall, which occurs uniformly through the year, is 800 mm. At the upstream end, the catchment elevation is 900 m AHD, mildly sloping to 600 m AHD at the catchment outlet. The main vegetation types are eucalyptus forest (less than 30% foliage cover) and herbaceous grasses. The catchment has duplex soils with a sandy or loamy A-horizon and bleached clayey subsurface soils.

Jimmy Creek at Jimmy Creek is located in the Glenelg River Basin in the south-west coast of Victoria. It has a catchment area of 23 km^2 and is one of the smaller catchments used in this study. The mean annual runoff in the catchment is 3700 ML (160 mm) and the mean annual rainfall, which falls uniformly through the year, is 650 mm. The average daily maximum summer temperature is 26°C and the average daily maximum winter temperature is 12°C. It has steep slopes (400–900 m AHD) and is covered predominantly by low eucalyptus trees (lower than 10 m). The catchment has thick sandy surface soils with highly impermeable clay subsoils.

Davey River downstream of Crossing River is located in the South-West Coast Basin in Tasmania, and with a catchment area of 686 km^2 is the largest catchment used in this study. The catchment has a runoff coefficient greater than 90%, with a mean annual rainfall (65% of which occurs in the winter period from May to October) of 2100 mm contributing to a mean annual runoff of 1 390 000 ML (2000 mm). It is possible that the rainfall data may have been underestimated, although the catchment may be receiving water from areas outside the catchment surface boundary. The winter months can be cold, with average daily maximum temperatures of 9°C, and the average maximum daily temperature in summer is 19°C. The catchment rises from 200 m AHD close to the coast to 1100 m AHD. It is covered by tussocky grasses and graminoids and has predominantly uniform coarse-textured sandy soils.

Dandongadale River at Matong North has a catchment area of 182 km^2 and is located in the Ovens River Basin (which drains into the Murray–

Darling system) in Victoria. The catchment has steep slopes (300–1600 m AHD) and is close to the snow fields (snow occurs on 10% of the raindays) of Victoria. The daily maximum temperatures range from 10°C in winter to 25°C in summer in the lower parts of the catchment and from 2°C to 17°C in the higher lands. The annual runoff is 70 000 ML (380 mm) and the mean annual rainfall is 1300 mm, with 65% of the annual total falling in the winter period. The catchment is covered predominantly by eucalyptus forest (more than 50% foliage cover) and has duplex soils with a hard-setting loamy A-horizon abruptly changing to clayey subsoils.

Kanyaka Creek at Old Kanyaka has a catchment area of 180 km^2 and is located in the Willochra River Basin in South Australia. It has an arid climate, with an annual rainfall of 300 mm (70% of which falls over the winter period) contributing to an annual runoff of only 330 ML (2 mm). Kanyaka Creek is ephemeral, with the daily streamflows being less than 1 ML for 99% of the time and zero for 43% of the time (see Table 1). The average daily maximum winter temperature is 16°C and the average daily maximum summer temperature is 34°C. The catchment has a mild slope (200–600 m AHD) and is covered mainly by acacia (of more than 2 m in height) and shrubs. The Kanyaka Creek catchment has predominantly deep sandy soils.

Canning River at Glen Eagle is located in the Swan Coast in south-west Western Australia. It has a catchment area of 544 km^2 and is the second largest catchment used for this study. The annual runoff is 8700 ML (20 mm) and the annual rainfall is 800 mm, with more than 50% of the rainfall occurring in the three winter months (June–August). The daily streamflow is zero for approximately 50% of the time, and although the highest recorded monthly streamflow over the period of data used for this study is 17 000 ML (more than twice the mean annual runoff), the monthly streamflow volume is zero for approximately 40% of the time. The catchment has a Mediterranean climate, with average daily maximum temperatures ranging from 16°C in winter to 31°C in summer. The catchment area is relatively flat (300–400 m AHD) and is predominantly covered by medium-height eucalyptus trees. It has predominantly yellow duplex soils with a hard-setting loamy A-horizon and a weakly pedal clayey B-horizon.

Mitchell Grass at Richmond is located in the Flinders River Basin in central–inland Queensland. The catchment area is only 3 km^2 and is the smallest used for this study. The average maximum daily temperatures range from 26 to 37°C. The mean annual rainfall is 450 mm, more than 60% of which falls in the three summer months (December–February). The mean annual runoff is only 50 ML (15 mm), with non-zero monthly runoff recorded for only eight of the 144 months of records used for this study. Non-zero daily streamflow is recorded for less than 1% of the time, and the highest recorded daily streamflow over the period of data used for this study is 120 ML (more than twice the mean annual runoff). The catchment is at 200 m AHD and has predominantly cracking clay soils.

Optimisation of model parameters

Objective functions

The idea behind the model calibration is to select parameter values to minimise the differences between the simulated and recorded streamflows. There are various criteria that can be used to measure model performance, and the criteria chosen should be able to reflect the relative merits of the various modelling approaches in simulating various aspects of streamflow. For instance, a model may reproduce peak flows satisfactorily, but may be poor in its simulation of low flows. A modelling approach may not be able to simulate daily streamflows satisfactorily, although it may be able to predict flow volumes over longer time periods adequately. In this study, parameter values are optimised to minimise the values of the following two objective functions:

$$\mathrm{OBJ1} = \sum_{i=1}^{n} (\mathrm{SIM}_i - \mathrm{REC}_i)^2 \tag{8}$$

$$\mathrm{OBJ2} = \sum_{i=1}^{n} (\mathrm{SIM}_i^{0.2} - \mathrm{REC}_i^{0.2})^2 \tag{9}$$

where SIM_i and REC_i are the simulated and recorded streamflows over period i, and n is the number of time periods simulated.

The first objective function, OBJ1, is the commonly used sum of squares of the differences between simulated and recorded streamflows; it will place more importance on the high flows and is useful in reflecting the ability of the models to estimate catchment yields. The second objective function, OBJ2, provides some weighting to reflect also the simulation of low flows.

Optimisation procedure

It is difficult to find a true ‘global optimum’ set of parameter values, and the difficulty increases as the number of model parameters increases. There are three major reasons for this. First, discontinuities are common in the response surface of rainfall–runoff models (mainly caused by the use of constraints to prevent parameters from taking unrealistic values), and an optimisation run may be trapped in one of the discontinuities, leading to the choice of a 'local optimum' set of parameter values (see Johnston and Pilgrim, 1976). Second, there is usually a high interdependence between various parameters of a many-parameter model. Third, the ordinary least-squares (OLS) assumptions, on which optimisation methods are based, are seldom satisfied. The OLS assumptions are that the error terms, $\mathrm{SIM}_i - \mathrm{REC}_i$, have zero mean and constant variance (the magnitudes of $\mathrm{SIM}_i - \mathrm{REC}_i$ are similar for all flow volumes), are mutually uncorrelated (not time dependent) and are normally distributed (see Clarke (1973) and Kuczera (1983)). The use of the objective function described by Eq. (8) violates the constant variance assumption, as the error term tends to grow as the flow becomes larger. The exponent 0.2 is used in Eq. (9) as it generally leads to constant variances (values of $\mathrm{SIM}_i^{0.2} - \mathrm{REC}_i^{0.2}$ are similar for all flow volumes) in many of the temperate catchments where models have been applied by the authors.

The optimum set of parameter values selected by an optimisation run is dependent on the starting point (choice of the initial parameter values), the criterion used to terminate the optimisation run and the steps chosen to perturb the parameter values. Although it is difficult to find a true 'global optimum', many optimisations runs with different starting points and different parameter perturbations can increase the likelihood of obtaining parameter values close to the 'global optimum'. In this study, the parameters are optimised using a pattern search optimisation procedure (see Hooke and Jeeves (1961) and Monro (1971)). The pattern search approach is chosen because it is more likely to find accurate parameter estimates compared with the gradient (Newton) methods (mainly because of the lack of robustness in the gradient methods in handling discontinuities in the response surface), although the gradient methods use less computer time (see Hendrikson and Sorooshian (1988) and Jayasuriya (1991)). Many optimisation runs are performed for each calibration using different initial parameter values, which are based on catchment characteristics and 'educated' guesses, and different parameter perturbations.

Simulation periods

Seven simulations are carried out on each catchment. The first six simulations estimate daily, monthly and annual flows, with the parameter values optimised to minimise the values of the two objective functions described by Eqs. (8) and (9). The entire period of the available record listed in Table 1 is used to calibrate the models to include as large a range of climatic characteristics as possible. In the seventh simulation, models are calibrated using only the first half of the available record, with the parameters optimised to minimise the value of OBJ1. The optimised parameter values are then used to simulate the flows in the second half of the available record to investigate the ability of the models in predicting monthly catchment yields for an independent test period. In all simulation runs, the first year of simulation is ignored because the time-series methods require rainfall records for previous time steps, and to allow storages in the conceptual models to reach equilibrium levels.

The IHACRES (complex time-series), SFB (simple conceptual) and MODHYDROLOG (complex conceptual) models are always operated on a daily time step using daily data (to estimate the daily, monthly and annual flows), whereas the simulations with the other three modelling approaches are carried out over the time steps for which the flow simulations are required (i.e. monthly runoff is related directly to monthly rainfall and annual runoff is related to annual rainfall).

Number of model parameters

In the simple polynomial (Eq. (1)) and Tsykin time-series equations (Eq. (3)), an extra parameter is used only if it improves the value of the objective function by more than 2%. In the simple polynomial equation, the use of three parameters (i.e. runoff related to the square of rainfall) is generally sufficient. In the Tsykin time-series equation, up to 10 parameters are used for the simulation of daily flows (i.e. runoff related to rainfall which occurred over the previous 8 days), up to seven parameters are used for the simulation of monthly flows (i.e. runoff related to rainfall which occurred over the previous 5 months) and up to three parameters are used for the simulation of annual flows. In general, more parameters are used for the ephemeral catchments (Catchments 509503, 616065 and 915001 — see Table 1), and for the simulations to minimise the 'lowflow' objective function, OBJ2.

The tanh equation has two parameters and the SFB model uses three parameters. The IHACRES model, in the form used for this study, has seven parameters. Seventeen parameters in MODHYDROLOG are optimised for this study, although Chiew and McMahon (1993b) have shown that the use of fewer parameters (nine or fewer) gives practically the same results, particularly in temperature catchments.

Model complexities and computing times

The computing time required to run the models is dependent on the complexity of the model algorithms and the number of time steps. However, with current computers, the simulation of up to 20 years of daily flows using the conceptual rainfall–runoff model, MODHYDROLOG, takes less than 11 s (the times quoted in this paper are approximate average interactive computing times on the VAX 11/750, PC 486 and HP9000/850), with simulations using the simple equations being faster.

However, in an optimisation run, many simulations (iterations) are performed as the parameters are perturbed and new values of objective function are calculated. The time required to complete an optimisation run is dependent on the time required for a single simulation run, the number of model parameters (more time is required if more parameters are to be perturbed), and the choice of initial parameter values (less time is required if initial values are close to the optimum). The approximate times required to complete an optimisation run for the six models are given in Table 2. In addition, many optimisation runs are performed for each model calibration (with different initial parameter values used and different perturbations applied to the parameters) to give the calibration process a higher chance of finding the 'global optimum'. The average actual modelling times spent optimising the model parameters for this study are also given in Table 2.

Many optimisation runs can be easily carried out for the simple polynomial and tanh equations, as each run takes less than 1 min. In addition, because the two equations have few parameters, the 30 min spent for each calibration should lead to the 'global optimum' set of parameter values. The same applies to the simulations of monthly and annual flows with the Tsykin equation. However, optimisation runs for the simulation of daily flows using the Tsykin equation can take up to 12 min (as more parameters and time steps are used), and although the 1 h spent calibrating the model should lead to parameter values close to the optimum, additional effort may improve the parameter estimates, particularly in the ephemeral catchments. The simple polynomial, tanh and Tsykin equations are easy to apply (simple data input and easy computer programming) and require little hydrological expertise. However, as with the applications of the other models, experience with optimisation procedures is essential.

The SFB model has only three parameters and although it is always operated on a daily time step, the time required for an optimisation run is relatively short (3–7 min). In addition, the authors are experienced in the use of the SFB model. The 1 h spent optimising the model parameters for each calibration (more than 20 different optimisation runs are performed — see comment 'c' in Table 2) should therefore lead to the 'global optimum' set of parameter values. The SFB model has more algorithms compared with the simple equations discussed in the previous paragraph, and the parameters are also purported to be related to catchment characteristics. As such, the application of the SFB model requires some experience in rainfall–runoff modelling.

Table 2
Computing times required for model calibrations

	Time required[a] for one simulation run (s)	Time required[b] for one optimisation run (min)	Time taken[c] for one calibration process (h)
Simple polynomial equation	3–4 (< 1)[d]	< 1	0.5
Tanh equation (simple process equation)	3–4 (< 1)	< 1	0.5
Tsykin equation (simple time-series equation)	4–5 (< 1)	6–12 (< 1)	1 (0.5)
IHACRES (complex time-series model)	8–11	8–15	1.5–2
SFB (simple conceptual model)	6–9	3–7	1
MODHYDROLOG (complex conceptual model)	8–11	20–40	2[e]

[a] The times given in this table are average interactive computing times (for simulation of 10–20 years of daily flows) on the VAX 11/750, PC 486 and HP 9000/850.
[b] Many simulations (iterations) are performed by the computer in an optimisation run as parameters are perturbed and new values of objective function calculated.
[c] A number of optimisation runs was carried out for each calibration process (using different starting points and different parameter perturbations) to increase the likelihood of finding the 'global' optimum. (Note that the number of optimisation runs for each calibration process is not the time in the third column divided by that in the second column because several optimisation runs can be carried out concurrently (although only two or three computers are used simultaneously at any one time, as a better choice of initial parameter values for an optimisation run can usually be obtained by inspecting the optimum values estimated by previous optimisation runs).)
[d] The simulations of monthly and annual flows with the polynomial, tanh and Tsykin equations use less computing time than the simulations of daily flows. This is because these equations relate the monthly and annual runoff directly to the monthly and annual rainfall, respectively, the monthly and annual simulations therefore having fewer time steps than the daily simulations. The values in parentheses represent the times required for the application of these equations to simulate monthly and annual flows.
[e] The authors have considerable experience with the application of MODHYDROLOG, and the time required to calibrate adequately a complex conceptual rainfall–runoff model can take much longer.

MODHYDROLOG has 17 parameters, some of which are interdependent whereas other can take a large range of values (see Chiew and McMahon, 1993b). Consequently, many optimisation runs may be required before parameter values close to the optimum can be obtained. As a single optimisation run of MODHYDROLOG can take up to 40 min, considerable time and effort are required to calibrate MODHYDROLOG. In addition, as the model algorithms are complex, more programming effort is required than for the other modelling approaches. Nevertheless, the authors have considerable experience with the application of MODHYDROLOG (including previous applications of the model to the eight catchments used in this study as well as 20 other catchments throughout Australia – see Chiew and McMahon (1993b), and the parameter values obtained for this study should also be close to the 'global optimum'. However, the 2 h calibration time listed in Table 2 is not a clear indication of the time required to calibrate a complex conceptual rainfall–runoff model, and without any prior calibration runs on the same catchments, the model calibration could take more than five times longer. In addition, considerable time must be spent understanding the model, as with 19 parameters, an appreciation of the model parameters and algorithms is essential before MODHYDROLOG (or any other complex conceptual rainfall-runoff model) can be 'meaningfully' used.

Approximately 8–15 min is required to complete an optimisation run with IHACRES. Nevertheless, the $1\frac{1}{2}$–2 h spent for each IHACRES model calibration (more than 20 different optimisation runs are performed) should give parameter estimates that are close to the optimum, although the authors believe that the simulation of the slow flow components and the simulations in the ephemeral catchments could be improved. The computer programming of the equations in IHACRES is simpler than the programming of the model algorithms in SFB (and therefore MODHYDROLOG), although it is more difficult to apply IHACRES than SFB (but simpler compared with MODHYDROLOG). This is because there are more parameters in IHACRES than in SFB, and unlike the conceptual rainfall–runoff models, the empirical parameters in IHACRES (τ and p) can take a large range of values, as they are directly related to the magnitude of rainfall and runoff.

Optimised parameter values

The optimised parameters in this study took a wide range of values over the several catchments. For the simple equations and time-series methods, they ranged over several orders of magnitude, as they are directly related to the magnitudes of rainfall and runoff. Model calibrations against the two objective functions, OBJ1 and OBJ2, also led to very different optimised parameter values. Although the IHACRES, SFB and MODHYDROLOG models are always operated on a daily time step, optimised parameter values for the seven simulations can differ by more than 100%. However, the use of parameter values optimised in one simulation (particularly the daily and monthly simulations) on another simulation generally (although not always) led to only a slightly poorer value of the objective function compared with the value obtained using optimised parameter values for that simulation. Nevertheless, it is not the intention of this study to investigate the parameters of the individual models, and for this reason, the optimised parameter values are not given. Detailed descriptions of the parameters and possible relationships between model parameters and the catchment climatic and physical characteristics can be found in the references given in the earlier section describing the modelling approaches.

Comparison of model simulations

Summary of results

The relative performance of the modelling approaches is best analysed by comparing the values of OBJ1 and OBJ2. The plots in Fig. 5 show the values of the objective functions for the six modelling approaches for the seven simulations in the eight catchments, relative to the lowest value obtained (given by one of the six models) for that particular simulation. The plots in Fig. 5 provide more information than a direct comparison of the actual values of the objective functions because the values of the objective functions for the simulations in the various catchments can differ by several orders of magnitude, as they are dependent on the flow volumes. In the following discussions, the catchments will be indicated by the 'catchment numbers' which represent the streamflow gauging stations at the catchment outlets (see Table 1).

The adequacy of the catchment streamflow yields estimated by the six modelling approaches is summarised in Tables 3 and 4. The categories used to describe the streamflow estimates ('perfectly acceptable simulation', 'acceptable simulation' and 'unacceptable simulation' — see also Figs. 8 and 9) are based on the average result from a survey conducted by Chiew and McMahon (1993d), where 63 participants throughout Australia working in the field of hydrology and water resources assessed the adequacy of 112 monthly streamflow simulations for use in catchment and reservoir yield analyses. Flow estimates classified as 'perfectly acceptable simulation' in Tables 3 and 4 have a coefficient of efficiency greater than 0.9 (with mean simulated flow always within 10% of mean recorded flow), and flow estimates classified as 'acceptable simulation' have a coefficient of efficiency greater than 0.6 (with mean simulated flow always within 15% of mean recorded flow). The coefficient of efficiency, E (see Aitken, 1973), is similar to the coefficient of determination, R^2, but unlike R^2, which measures the degree of association between the simulated and recorded flows, E measures directly the ability of

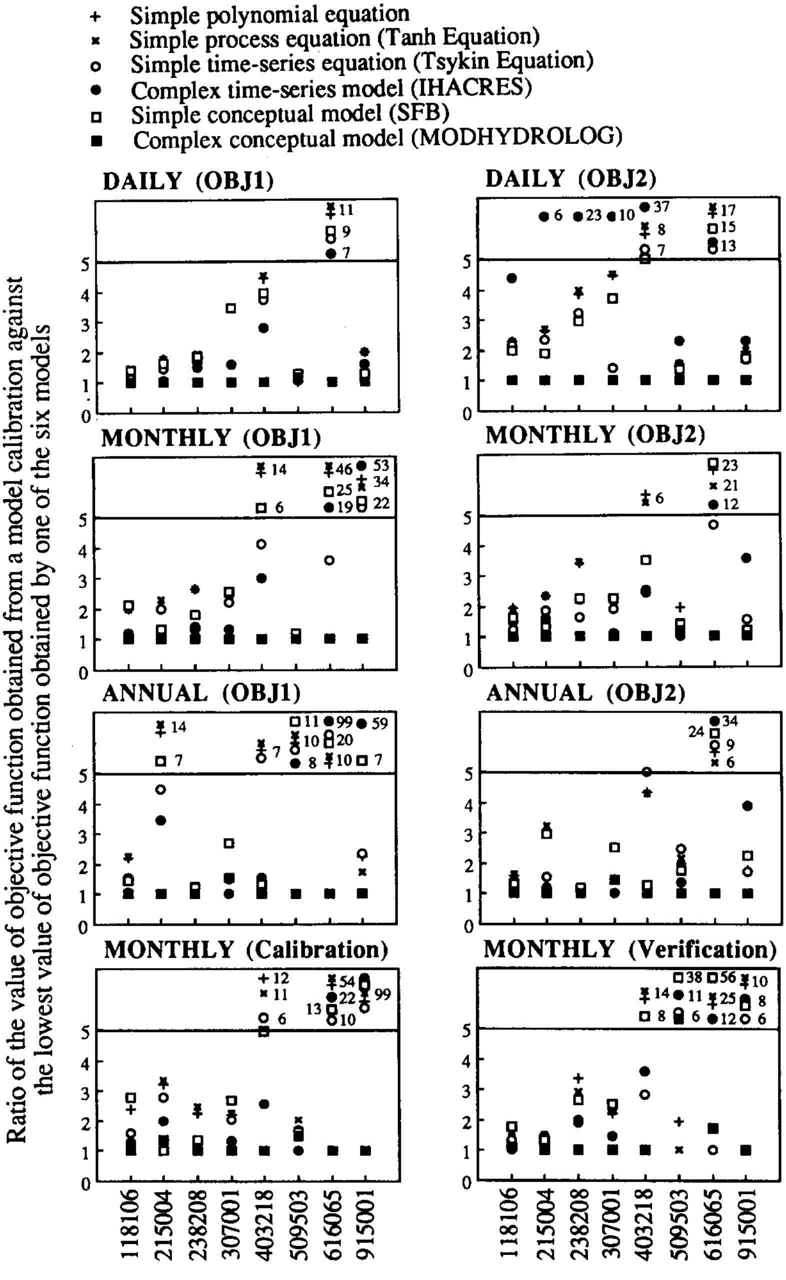


Fig. 5. Relative values of the objective functions obtained by the six modelling approaches for seven simulations in eight unregulated catchments.

Table 3
Adequacy of the daily, monthly and annual catchment streamflow yields simulated by the six modelling approaches with parameters optimised to minimise the values of the two objective functions.

	Catchment no.							
	118106	215004	238208	307001	403218	509503	616065	915001
Daily (OBJ1)								
Simple polynomial equation								
Simple process equation								
Simple time-series equation				B				
Complex time-series model								
Simple conceptual model								
Complex conceptual model		B		B	B		A	
Monthly (OBJ1)								
Simple polynomial equation				B				B
Simple process equation				B				B
Simple time-series equation	B		B	B	B		A	B
Complex time-series model	B	B	B	A	B			
Simple conceptual model	B	B	B	B	B			B
Complex conceptual model	B	B	B	A	A		A	A
Annual (OBJ1)								
Simple polynomial equation	B	B		B	B		A	A
Simple process equation	B	B		B	B		A	A
Simple time-series equation	B	A	B	B	B		A	A
Complex time-series model	B	A	B	A	A			
Simple conceptual model	B	B	B	B	A		A	A
Complex conceptual model	B	A	B	A	A	A	A	A

Daily (*OBJ2*)								
Simple polynomial equation								
Simple process equation								
Simple time-series equation								
Complex time-series model								
Simple conceptual model		B						
Complex conceptual model		B						
Monthly (*OBJ2*)								
Simple polynomial equation				B				
Simple process equation				B				
Simple time-series equation				B	B			B
Complex time-series model				A	B			
Simple conceptual model	B	B	B	B	B			B
Complex conceptual model	B	B	B	A	A		A	A
Annual (*OBJ2*)								
Simple polynomial equation	B	B		B	B		B	B
Simple process equation	B	B		B	B		A	A
Simple time-series equation	B	A		B	B		B	B
Complex time-series model	B	A		A	A			
Simple conceptual model	B	B	B	B	A		A	B
Complex conceptual model	B	A	B	A	A	B	A	A

A, Perfectly acceptable simulation (coefficient of efficiency is greater than 0.9 and mean simulated flow is within 10% of mean recorded flow)..

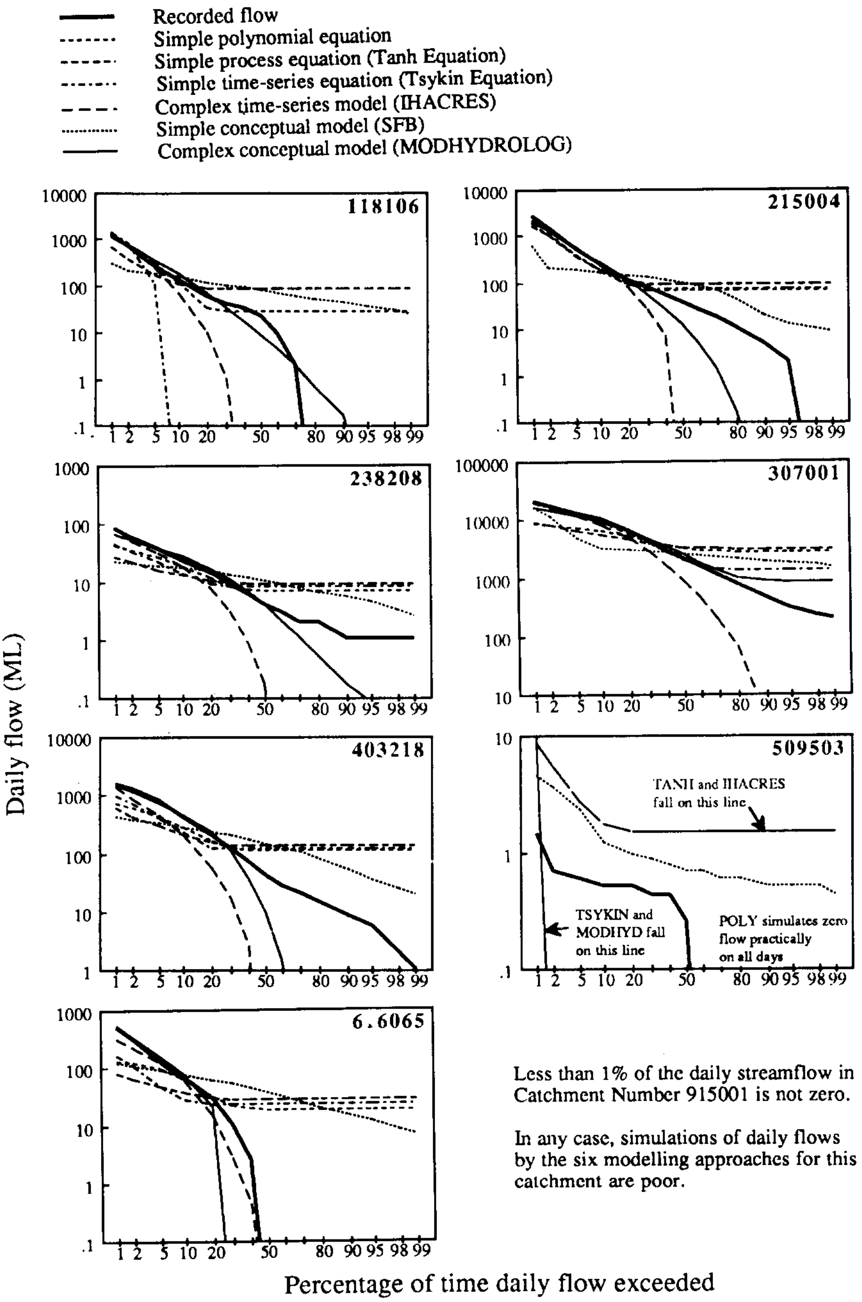
B, Acceptable simulation (coefficient of efficiency is greater than 0.6 and mean simulated flow is within 15% of mean recorded flow).

Table 4
Adequacy of the monthly catchment yields simulated by the six modelling approaches for the calibration period (parameters optimised using the first half of the record) and for the verification period (optimised parameter values for the calibration period applied directly to the second half of the record)

	Catchment no.							
	118106	215004	238208	307001	403218	509503	616065	915001
Calibration								
Simple polynomial equation	B			B				A
Simple process equation	B			B				A
Simple time-series equation	B			B	B		B	A
Complex time-series model	A		B	A	B			B
Simple conceptual model	B	B		B	B		B	A
Complex conceptual model	A	B	B	A	A		A	A
Verification								
Simple polynomial equation				B				
Simple process equation				B				
Simple time-series equation				B	B		A	
Complex time-series model			B	A	A			
Simple conceptual model		B	B	B	B		B	
Complex conceptual model		B	B	A	A		A	B

A, perfectly acceptable simulation (coefficient of efficiency is greater than 0.9 and mean simulated flow is within 10% of mean recorded flow).

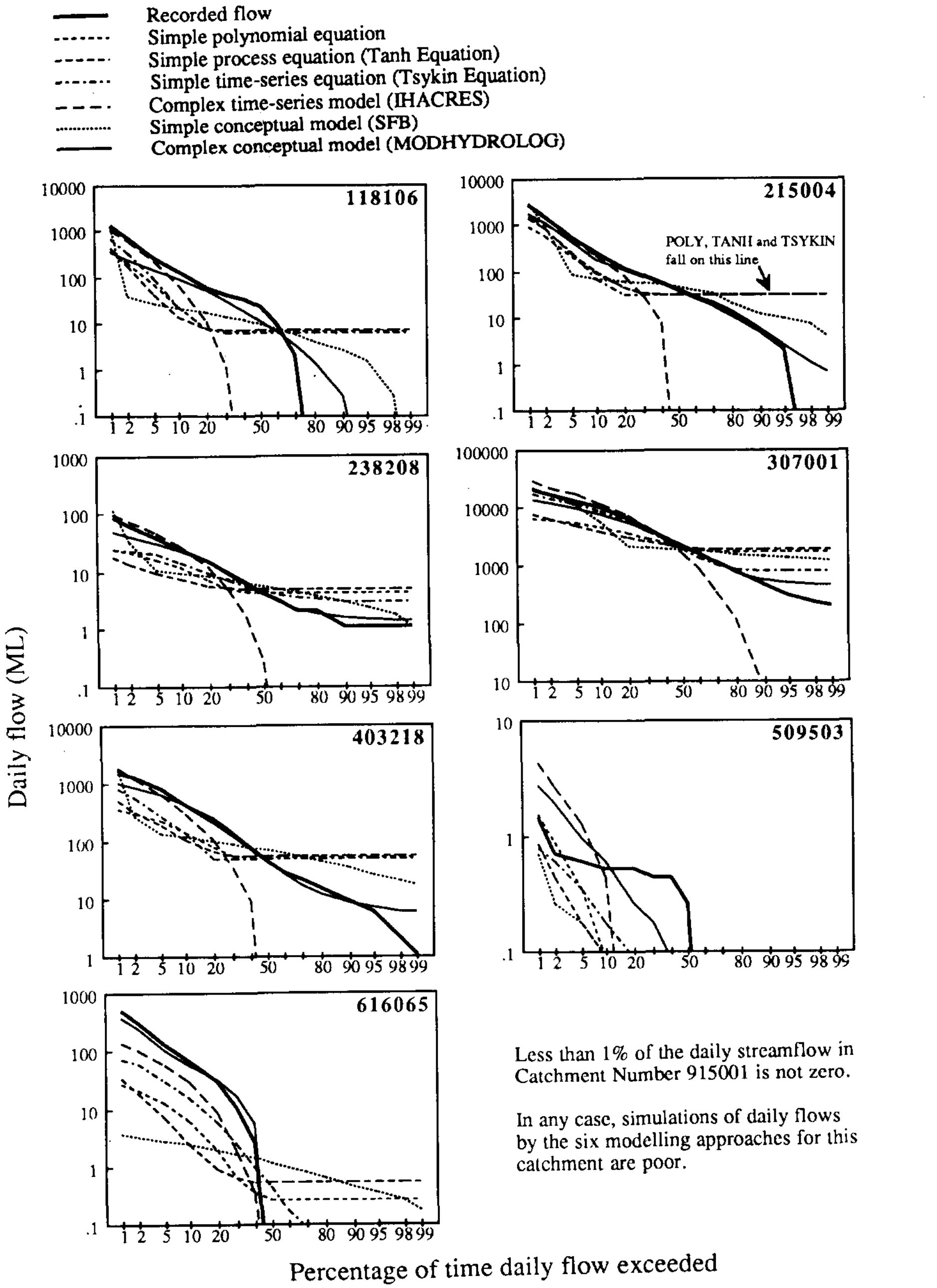
B, Acceptable simulation (coefficient of efficiency is greater than 0.6 and mean simulated flow is within 15% of mean recorded flow).



Less than 1% of the daily streamflow in Catchment Number 915001 is not zero.

In any case, simulations of daily flows by the six modelling approaches for this catchment are poor.

Fig. 6. Comparisons of flow duration curves of daily flows estimated by the six modelling approaches and the recorded daily flows (for model calibrations against OBJ1).



Less than 1% of the daily streamflow in Catchment Number 915001 is not zero.

In any case, simulations of daily flows by the six modelling approaches for this catchment are poor.

Fig. 7. Comparisons of flow duration curves of daily flows estimated by the six modelling approaches and the recorded daily flows (for model calibrations against OBJ2).

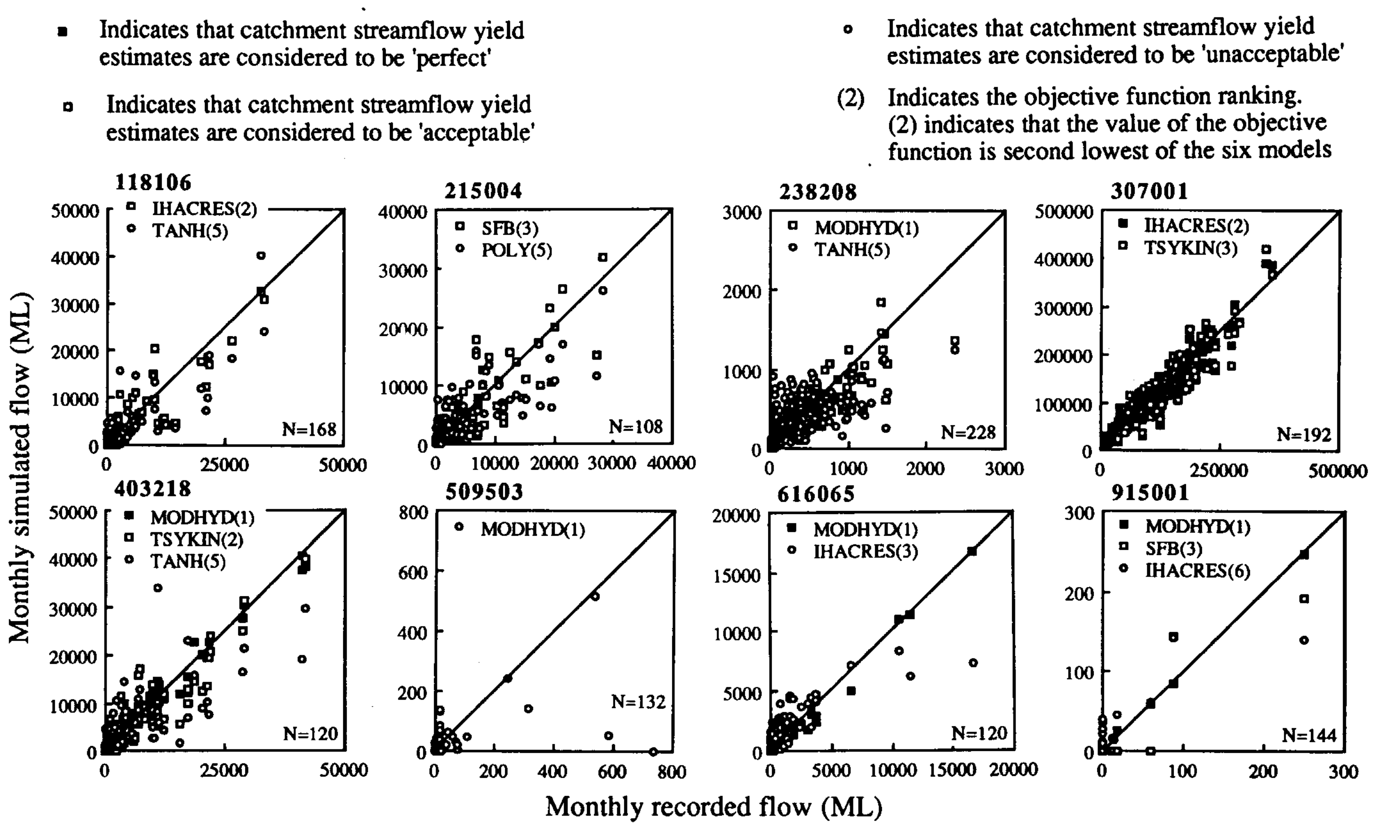


Fig. 8. Typical comparisons of monthly simulated and recorded flows.

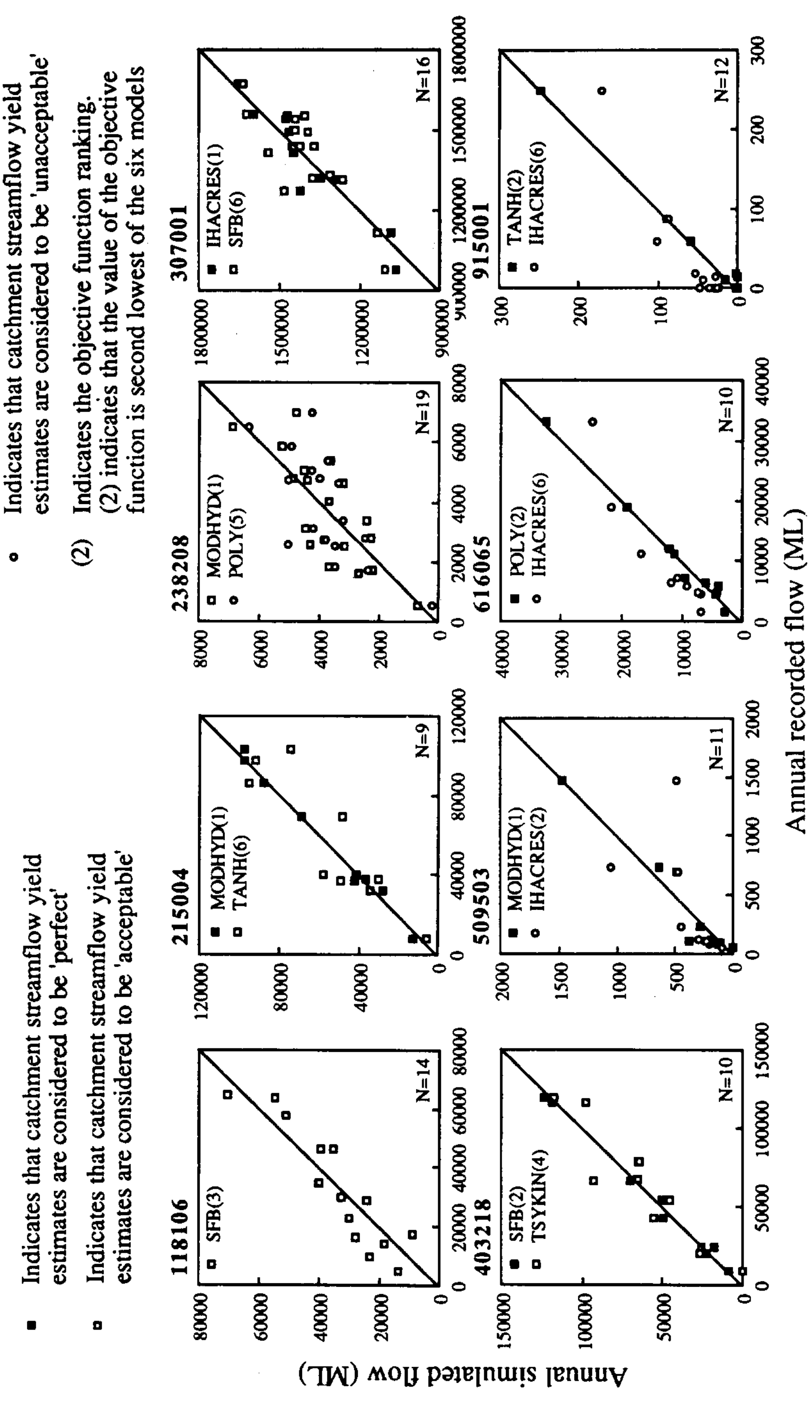


Fig. 9. Typical comparisons of annual simulated and recorded flows.

the model to reproduce the recorded flow ($E = 1.0$ therefore indicates that all the simulated flows are the same as the recorded flows).

Flow duration curves comparing daily flows estimated by the six modelling approaches with the recorded flows, for calibrations against OBJ1 and OBJ2, are given in Figs. 6 and 7, respectively. Although the flow duration curves are useful in providing an overall indication of the daily flow volumes estimated by the models, they cannot indicate whether a particular flow estimate is simulated for the same day on which it is recorded. The x–y plots in Figs. 8 and 9 compare typical simulated and recorded monthly and annual flows, respectively, for the model calibrations against OBJ1 (simulations for OBJ2 are practically the same — see Table 3 and later discussion). Unlike the flow duration curves, the x–y plots provide a direct comparison of the simulated and recorded flows for the same month (or year).

Simulation of catchment streamflow yield (parameters optimised to minimise the value of OBJ1)

OBJ1 reflects the simulation of the high flows, and therefore, the adequacy of catchment yield estimates (see Table 3). The complex conceptual rainfall–runoff model (MODHYDROLOG) performs best in practically all the simulations. It appears that MODHYDROLOG can provide 'acceptable' daily flow estimates for wet catchments (more than 30% of annual rainfall becomes runoff) which flow for more than 80% of the time (Catchments 215004, 307001 and 403218). The daily yields estimated by MODHYDROLOG for Catchment 616065 are also considered to be 'acceptable', with MODHYDROLOG practically reproducing the recorded 'high flows' (see flow duration curves for Catchment 616065 in Fig. 6). The daily flow volumes estimated by the other models are all considered to be 'unacceptable' (except for the simulation given by the Tsykin equation for Catchment 307001). Estimates of daily flows given by the six models for the two catchments (Catchments 509503 and 915001), where the daily flow is greater than 1 ML for less than 1% of the time, are extremely poor. In general, the complex time-series model (IHACRES) is second best (see Fig. 5) and the simple time-series equation (Tsykin) is third best in the simulation of daily yields, and the daily flows estimated by the polynomial and tanh equations and the simple conceptual model (SFB) are poor in all the catchments. It is also interesting to note that the flow duration curves (see Figs. 6 and 7) for the simple equations (polynomial, tanh and Tsykin) approach an asymptotically constant value in almost all the simulations. This is because the parameter, a (see earlier section describing the models) in the equations, which represents the maximum value of rainfall below which runoff would not occur, is optimised at a positive value (negative for the tanh equation) in the model calibrations, therefore effectively simulating runoff (= '*a*' mm) even on days when there is no rainfall (representing baseflow?).

The monthly catchment yields estimated by MODHYDROLOG are considered to be 'perfect' in four of the eight catchments and are 'acceptable' in seven catchments. Table 3 also indicates that, except for the polynomial and tanh equations, the other modelling approaches can provide 'acceptable' estimates of monthly yields in the wetter catchments (Catchments 118106, 215004, 238208, 307001 and 403218). In these catchments, the complex time-series model performs second best (values of objective function are within 20% of MODHYDROLOG in four of the five catchments), followed by the simple time-series equation and the simple conceptual model. The plots in Fig. 8 show typical comparisons of monthly simulated and recorded flows. It must be noted that, in many cases, estimates which are considered 'unacceptable' can still be used to provide an indication of the approximate volumes of runoff.

The annual catchment yields estimated by MODHYDROLOG are considered to be 'perfect' in six catchments and are 'acceptable' in all eight catchments (see Table 3). The relative values of OBJ1 in Fig. 5 for the simulation of annual streamflow also indicate that MODHYDROLOG performs best. However, the annual catchment yields estimated by all six modelling approaches are also considered to be 'acceptable' in almost all the simulations. The typical plots in Fig. 9 show that the models can generally provide adequate estimates of annual runoff.

Flow estimates for the dry 'ephemeral' catchments (509503, 616065 and 915001)

Unlike the other five catchments, Catchments 509503, 616065 and 915001 are dominated by long periods of low flows (see Table 1 and Fig. 3). Catchment 915001 flows for less than 1% of the time, with 94% of the monthly streamflow volume being zero. The daily streamflow in Catchment 509503 is greater than 1 ML for less than 1% of the time, and the daily streamflow in Catchment 616065 is greater than 1 ML for less than 50% of the time. In all three catchments, less than 4% of the annual rainfall becomes runoff.

The three catchments also show distinctly different rainfall–runoff characteristics. The hydrographs in Fig. 3 show only two significant monthly runoff events for Catchment 915001 during the period of data used for this study, both of which occurred when monthly rainfall exceeded 300 mm. This direct relationship between monthly rainfall and runoff explains why the simple equations (polynomial, tanh and Tsykin) can simulate satisfactorily the monthly runoff in the catchment, as these equations directly relate monthly runoff to monthly rainfall. On the other hand, the complex time-series model (IHACRES), which attempts to simulate the daily flows, does not give satisfactory monthly flow estimates for the catchment (see Figs. 8 and 9). However, the conceptual rainfall–runoff models (SFB and MODHYDROLOG), which also operate on a daily time step, do not suffer from the same limitations of IHACRES. This is mainly because, unlike the time-series model, the conceptual model (through the use of model storages for soil-moisture accounting) does not 'manipulate' directly the daily rainfall inputs. However, IHACRES, when applied on a monthly time step, could provide 'acceptable' estimates of monthly flows for Catchment 915001. This suggests that preliminary inspection of rainfall and streamflow hydrographs is extremely useful in selecting models and modelling time steps for a particular application.

Similarly, although the hydrographs in Fig. 3 do not show a clear relationship between rainfall and runoff in Catchment 616065, the plot in Fig. 4 indicates that annual runoff in the catchment can be easily related to annual rainfall. The polynomial and tanh equations cannot give satisfactory estimates of monthly flows but can simulate satisfactorily the annual flows (see Fig. 9). The complex time-series model cannot simulate adequately either the monthly or the annual catchment yield. There is no clear rainfall–runoff relationship for Catchment 509503, and except for the annual estimates given by MODHYDROLOG, all model simulations for the various time periods are extremely poor.

Simulation of high and low flows (parameters optimised to minimise the value of OBJ2)

Unlike OBJ1, OBJ2 attempts to reflect also the simulation of the low flows. The various simulations obtained through model calibrations against OBJ1 and OBJ2 are clearly indicated by the daily flow duration curves in Figs. 6 and 7. The plots in Fig. 6 show that, when the models are calibrated against OBJ1, they attempt to simulate the high flows adequately at the expense of the low flows. When calibrated against OBJ2, the simulation of the low flows is much better, whereas the simulation of the high flows becomes poorer. The total streamflow volumes for daily simulations with model calibrations against OBJ2 are generally between 60% (for the polynomial, tanh and Tsykin equations) and 80% (for the IHACRES, SFB and MODHYDROLOG models) of the total volumes obtained through model calibrations against OBJ1. The adequacy of catchment yields estimated through model calibrations against OBJ2 is summarised in Table 3 for comparative purposes, and has little significance because, in applications where estimates of catchment yields are important, the models should be calibrated against OBJ1.

The plot in Fig. 5 comparing the values of OBJ2 for daily flow simulations and the flow duration curves in Fig. 7 indicate that the complex conceptual rainfall–runoff model (MODHYDROLOG) gives, by far, the best simulation of the low flows compared with the other modelling approaches. The simple conceptual model (SFB) usually performs second best and the simple time-series equation (Tsykin) comes in third. The daily lowflow simulations given by the complex time-series model (IHACRES) are extremely poor (see Fig. 7, and also Fig. 6); this is mainly due to the difficulty in optimising the model parameters describing the 'slow flow' component of runoff (A.J. Jakeman, personal communication, 1992).

Although MODHYDROLOG still performs best for the monthly flow simulations (see Fig. 5), the simulations from the other modelling approaches (including IHACRES) are comparable with those of MODHYDROLOG. The values of OBJ2 obtained by the Tsykin equation and the IHACRES and SFB models are within 50% of the values of OBJ2 obtained using MODHYDROLOG in most of the catchments. The monthly catchment yields estimated through model calibrations against OBJ2 are only 10% (for the IHACRES, SFB and MODHYDROLOG models) to 20% (for the polynomial, tanh and Tsykin equations) smaller than the yields obtained through model calibrations against OBJ1. This explains why the classifications used to describe the adequacy of monthly catchment yields estimated through model calibrations against OBJ1 and OBJ2 given in Table 3 are practically the same. The annual flow simulations for model calibrations against OBJ1 and OBJ2 are also almost the same. This suggests that, when adequate simulation of low flows is required, the use of an objective function that can reflect the simulation of low flows (e.g. OBJ2 or a log objective function) is essential for daily flow simulations, although the use of a suitable 'lowflow objective function' becomes less important as the period over which the streamflow estimates is required increases.

Flow simulations for an independent test period

Although the six simulations (over three time periods for model calibrations against two objective functions) discussed thus far are based on the optimisation of model parameters using the entire length of record, the ability of the modelling approaches to simulate monthly catchment yields for an independent test period is also investigated. In these simulations, the model parameters are optimised using only the first half of the record (for monthly flows and OBJ1), whereas the second half of the record is used as an independent test data to investigate the ability of the optimised parameter values in estimating runoff for this 'verification' period. This follows the procedure proposed by Klemes (1986), although the reverse procedure of calibrating against the second half of the record and using the first half of the record as independent test data is not carried out here.

The plots in Fig. 5 indicate that the relative performance of the modelling approaches in simulating monthly streamflow when model parameters are optimised using the entire period of record and using only the first half of the record is practically the same, although Table 4 indicates that the flow estimates obtained through model calibrations against the longer record are slightly better. The relative performance of the modelling approaches in estimating streamflow for the calibration and verification periods is also practically the same. Table 4 indicates that the results for the category used to describe the adequacy of the monthly yield estimated for the calibration and verification periods are almost the same, with the exception of Catchments 118106 and 915001. The optimised parameter values for Catchment 915001 cannot estimate the flows in the verification period because the models are calibrated against only a single significant flow event (see Fig. 3). As for Catchment 118106, the streamflows during the verification period are generally more difficult to simulate. Optimisation of model parameters using the second half of the record directly also could not provide monthly flow estimates that are 'acceptable' (with the exception of MODHYDROLOG). These simulations therefore indicate that, with the time-series and conceptual rainfall–runoff modelling approaches, a model which can be calibrated adquately can generally be used with sufficient confidence to predict flows for another period, provided that a sufficiently long data set is used to calibrate the model. A longer record is required to calibrate the model for semi-arid and arid catchments, where significant flow events are fewer, and for catchments with highly variable climatic conditions.

Conclusions

Six rainfall runoff modelling approaches – simple polynomial equation, simple process equation (tanh equation), simple time-series equation (Tsykin equation), complex time-series model (IHACRES), simple conceptual model (SFB) and complex conceptual model (MODHYDROLOG) — are compared in this paper, with the models used to simulate daily, monthly and annual flows in eight unregulated catchments. The simple equations (polynomial, tanh and Tsykin) are easy to apply and require little expertise in hydrology, whereas the application of the other three models requires some understanding of the rainfall–runoff process. The complex conceptual rainfall–runoff model is the most difficult to use because it requires long computing times (mainly for the optimisation of parameters), and a good understanding of the model is essential before it can be 'meaningfully' used.

The complex conceptual model can provide adequate estimates of daily flows for wet catchments (more than 30% of annual rainfall becomes runoff) whereas simulations of daily flows for the drier catchments are generally poor. The other modelling approaches cannot provide consistently adequate daily flow estimates. The complex conceptual model also gives, by far, the best simulation of the daily low flows compared with the other modelling approaches. For this reason, the use of a complex conceptual rainfall–runoff model is essential for the simulation of daily flows.

The complex conceptual model can simulate adequately monthly flows in almost all catchments, with the exception of arid catchments where less than 1% of annual rainfall becomes runoff. Annual flows estimated by the complex conceptual model are almost the same as the recorded flows in all eight catchments. However, the time-series approaches and the simple conceptual model also provide satisfactory estimates of monthly and annual streamflow for the wetter catchments (where more than 10% of annual rainfall becomes runoff and streams flow for more than 70% of the time). As it is easier to use these approaches than the complex conceptual model, the simpler methods may be used to estimate monthly and annual catchment yields in the wetter catchments.

Acknowledgements

This study is part of a project funded by the National Greenhouse Advisory Committee through the Australian Greenhouse Research Grants Scheme. The climate data were provided by the National Climate Centre of the Australian Bureau of Meteorology and the streamflow data were obtained from the respective Australian State Water Agencies.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., 1986a. An introduction to the European Hydrological System–Système Hydrologique Européen, "SHE", 1. History and Philosophy of a physically-based, distributed modelling system. J. Hydrol., 87: 45–59.

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., 1986b. An introduction to the European Hydrological System–Système Hydrologique Européen, "SHE", 2. Structure of a physically-based, distributed modelling system. J. Hydrol., 87: 61-77.

Aitken, A.P., 1973. Assessing systematic errors in rainfall-runoff models. J. Hydrol., 20: 121-136.

Australian Bureau of Meteorology, 1991. Benchmark Stations for Monitoring the Impact of Climatic Variability and Change, Vols. 1-7. Water Resources Assessment Section, Hydrology Branch, Melbourne.

Beven, K., 1989. Changing ideas in hydrology — the case of physically-based models. J. Hydrol., 105: 157-172.

Beven, K.J., Calver, A. and Morris, E.M., 1987. The Institute of Hydrology Distributed Model. Rep. 81, Institute of Hydrology, Wallingford, UK.

Boughton, W.C., 1968. A mathematical catchment model for estimating runoff. J. Hydrol. (N.Z.), 7(2): 75-100.

Boughton, W.C., 1984. A simple model for estimating the water yield of ungauged catchments. Civ. Eng. Trans., Inst. Eng. Aust., CE26(2): 83-88.

Budyko, M.I., 1977. Global'naja Ekologija (Global Ecology). Mysl, Moscow. Progress, London, 323 pp.

Burnash, R.J.C., Farral, R.L. and McGuire, R.A., 1973. A Generalised Streamflow Simulation System-Conceptual Modelling for Digital Computers. Joint Federal-State River Forecast Centre, Sacramento, USA, 204 pp.

Chiew, F.H.S. and McMahon, T.A., 1991. Improved modelling of the groundwater processes in MODHYDROLOG. Proc. Hydrol. and Water Resour. Symp., Perth, Western Australia, October 1991, Inst. Eng. Aust., Canberra, A.C.T., Nat. Conf. Publ., 91/22(2), pp. 492-497.

Chiew, F.H.S. and McMahon, T.A., 1993a. Detection of trend or change in annual flow in Australian rivers. Int. J. Climatol. (in press).

Chiew, F.H.S. and McMahon, T.A., 1993b. Application of the daily rainfall-runoff model MODHYDROLOG in to Australian catchments. J. Hydrol. (submitted).

Chiew, F.H.S. and McMahon, T.A., 1993c. Australian data for rainfall-runoff modelling and the calibration of models against streamflow data recorded over different time periods. Inst. Eng. Aust. Civ. Eng. Trans. (in press).

Chiew, F.H.S. and McMahon, T.A., 1993d. Assessing the quality of catchment streamflow yield estimates. J. Hydrol. (submitted).

Clarke, R.T., 1973. A review of some mathematical models used in hydrology, with observations on their calibration and use. J. Hydrol., 19: 1-20.

Crawford, N.H. and Linsley, R.K., 1966. Digital simulation in hydrology, Stanford Watershed Model IV. Stanford Univ. Dep. Civ. Eng. Tech., Rep., 39.

Freeze, R.A. and Harlan, R.L., 1969. Blueprint for a physically-based, digitally-simulated hydrologic response model. J. Hydrol., 9: 237-258.

Gan, K.C., McMahon, T.A. and Finlayson, B.L., 1990. Detection of climate trend in large basin discharge data. Centre for Environmental Applied Hydrology, University of Melbourne, 53 pp.

Haan, C.T., 1972. A water yield model for small watersheds. Water Resour. Res., 8(1): 58-69.

Hendrikson, J.D. and Sorooshian, S., 1988. Comparison of Newton-type and direct search algorithms for calibration of conceptual rainfall-runoff models. Water Resour. Res., 24: 691-700.

Hooke, R. and Jeeves, T.A., 1961. 'Direct Search' solution of numerical and statistical problems. J. Assoc. Comput. Mach., 8(2): 212-229.

Jakeman, A.J. and Hornberger, G.M., 1993. How much complexity is warranted in a rainfall–runoff model? Water Resour. Res. (in press).

Jakeman, A.J., Littlewood, I.G. and Whitehead, P.G., 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. J. Hydrol., 117: 275–300.

Jayasuriya, L.N.N., 1991. A methodology for estimating yield from small ungauged rural catchments, PhD thesis, Department of Civil and Agricultural Engineering, University of Melbourne, Vic., 349 pp.

Johnston, P.R. and Pilgrim, D.H., 1976. Parameter optimization for watershed models. Water Resour. Res., 12: 477–486.

Klemes, V., 1986. Operational testing of hydrological simulation models. Hydrol. Sci., 31(1): 13–24.

Kuczera, G., 1983. Improved parameter inference in catchment models: I, Evaluating parameter uncertainty. Water Resour. Res., 19: 1151–1162.

McMahon, T.A. and Mein, R.G., 1973. Storage–yield estimates with inadequate streamflow data. Proc. Symp. Design of Water Resour. Projects with Inadequate Data, Madrid, June 1993, IAHS–AISH Publ., 108(1), pp. 335–347.

McMahon, T.A., Finlayson, B.L., Haines, A.T. and Srikanthan, R., 1992, Global Runoff — Continental Comparisons of Annual Flows and Peak Discharges. Catena, Cremlingen-Destedt, Germany, 166 pp.

Monro, J.C., 1971. Direct search optimisation in mathematical modelling and a watershed model application. National Oceanic Atmospheric Administration, National Weather Service, U.S. Dept. of Commerce, NOAA, Silver Spring, MD, Tech. Memo. NWS HYDRO-12, 52 pp.

Moore, I.D. and Mein, R.G., 1975. An evaluation of three rainfall–runoff models. Proc. Hydrol. Symp., Sydney, May 1975, Inst. Eng. Aust., Sydney, N.S.W., Nat. Conf. Publ., 75/3, pp. 122–126.

Morton, F.I., 1983. Operational estimates of actual evapotranspiration and their significance to the science and practice of hydrology. J. Hydrol., 66: 1–76.

Nemec, J. and Rodier, J.A., 1979. Streamflow characteristics in areas of low precipitation (with special reference to low and high flows) in the hydrology of areas of low precipitation. Proc. Canberra Symp., December 1979, IAHS–AISH Publ., 128, pp. 125–140.

Porter, J.W. and McMahon, T.A., 1976. The Monash Model: User Manual for Daily Program HYDROLOG. Dept. of Civil Eng., Monash University, Vic., Res. Rep. 2/76, 41 pp.

Sittner, W.T., 1976. WMO project on intercomparison of conceptual models used in hydrologic forecasting. Hydrol. Sci. Bull. (IAHS), 21: 203–213.

Sukvanachaikul, Y. and Laurenson, E.M., 1983. An improved rainfall–runoff model for semi-arid regions. Proc. Hydrol. and Water Resour. Symp., Hobart, November 1983, Inst. Eng., Canberra, A.C.T., Aust., Nat. Conf. Publ., 83/13, pp. 108–112.

Tsykin, E.N., 1985. Multiple nonlinear statistical models for runoff simulation and prediction. J. Hydrol., 77: 209–226.

US Soil Conservation Service, 1972. SCS National Engineering Handbook, Section 4, Hydrology. US Government Printing Office, Washington DC, loose-leaf.

Weeks, W.D. and Hebbert, R.H.B., 1980. A comparison of rainfall–runoff models. Nordic Hydrol., 11: 7–24.

World Meteorological Organization, 1975. Intercomparison of conceptual models used in operational hydrologic forecasting. Operational Hydrol. Rep. 7, WMO, Geneva, 172 pp.