Journal of Hydrology, 153 (1994) 383–416

0022-1694/94/$07.00

[4]

Application of the daily rainfall–runoff model MODHYDROLOG to 28 Australian catchments

Francis Chiew*, Tom McMahon

Centre for Environmental Applied Hydrology, University of Melbourne, Parkville, Vic., Australia

(Received 12 October 1992; revision accepted 30 April 1993)

Abstract

The daily rainfall–runoff model, MODHYDROLOG, has been used extensively in Australia to estimate runoff from rainfall and potential evapotranspiration data. This paper describes the application of MODHYDROLOG to 28 catchments throughout Australia with different climatic and physical characteristics. Four simulations are carried out on each catchment, the simulations differing in the numbers of model parameters optimized in the model calibration. The study indicates that the use of nine (or fewer) model parameters is sufficient to give adequate estimates of streamflow, and the use of four or five parameters may be sufficient in temperate catchments and in applications where only approximate estimates of runoff are required. MODHYDROLOG is purported to be 'physically based' and this study also indicates 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 for this reason, MODHYDROLOG must always be calibrated in all modelling applications. Based on the general results from this study, recommendations are given in the Appendix to guide model users in optimizing and determining parameter values in MODHYDROLOG.

1. Introduction

Estimates of runoff are an essential component in the management of water resources. Reliable estimates of streamflows are required for catchment and reservoir yield analyses, to infill missing flow records, to extend streamflow sequences and for research into the understanding of hydrological processes. The daily rainfall–runoff model, HYDROLOG (Porter and McMahon, 1976), has been used extensively in Australia to estimate runoff from rainfall and potential evapotranspiration data. It has been tested on six catchments in

* Corresponding author.

SSDI 0022-1694(93)02328-U

southeastern Australia by Porter and McMahon (1975), and used by other modellers in semiarid and temperate catchments in southeastern Australia to extend recorded streamflow sequences (recent users include Sargent, 1986; Porter, 1988; Nathan and McMahon, 1988; Nandakumar, 1989). HYDROLOG has also been applied to tropical (Brown, 1987) and arid (Wong and Mustinov, 1987) catchments. Model comparison studies by Moore and Mein (1975) on four southeastern Australian catchments and by Weeks and Hebbert (1980) on three catchments in the southwest region of Western Australia indicate that HYDROLOG generally performs better or as well as other commonly used rainfall–runoff models (Stanford model, Sacramento model and Boughton model). Chiew et al. (1993a) shows that MODHYDROLOG gives much better estimates of streamflow on eight catchments throughout Australia compared with simpler conceptual models and time-series equations.

HYDROLOG was developed by Porter and McMahon (1976), while Chiew and McMahon (1991) modified the groundwater algorithms to improve the simulations of the stream–aquifer interaction and the groundwater seepage process (MODHYDROLOG). The model includes as many component parts as necessary to simulate the hydrological processes that can be described adequately in mathematical terms of physical significance. Algorithms that could extend the flexibility of the model but are not physically based are not included. For this reason, MODHYDROLOG is purported to be 'physically based' and Porter and McMahon (1976) provide recommended parameter values based on their experience in applying the model to various catchments in southeastern Australia. However, the parameters (19 parameters in MODHYDROLOG) can take a large range of values and should be optimized where possible. Sensitivity studies on the relative importance of the parameters in HYDROLOG have been carried out by Chiew and McMahon (1990) for a semiarid catchment and by Wong and Mustinov (1987) for an arid catchment, but these studies cannot provide general recommendations for parameter values as the results are applicable only to the particular catchments where the model has been tested.

This paper describes the calibration of MODHYDROLOG to reproduce the recorded streamflows at 28 unregulated catchments throughout Australia with different climatic and physical characteristics. All the model parameters are first optimized using a pattern search optimization procedure. A simple sensitivity analysis is then carried out to determine the relative importance of the model parameters. Based on the results from the analysis, the less important parameters are set to constant values and MODHYDROLOG (with fewer parameters) is re-calibrated for the 28 catchments. The stream-

Table 1
List of parameters in MODHYDROLOG

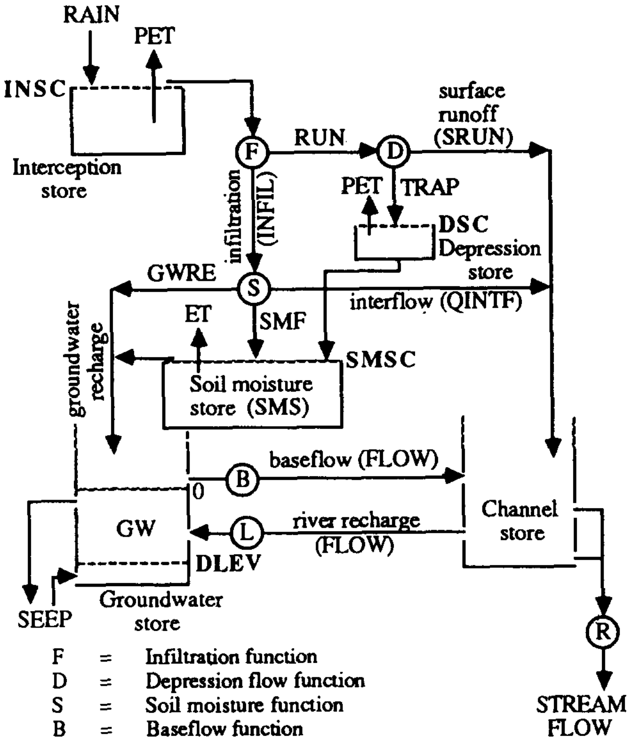
Parameter	Description
ADS	Fraction of total area which is depressional
CO	Routing coefficient
COEFF	Maximum infiltration loss parameter
CRAK	Constant of proportionality in the calculation of groundwater recharge
DLEV	Parameter used in deep seepage equation (represents 'water level' in the deep aquifer relative to the river)
DSC	Depression store capacity
EM	Maximum plant-controlled rate of evapotranspiration under non-limiting catchment and climatic conditions
INSC	Interception store capacity
*K*1	Constant of proportionality in linear part of stream–aquifer flow equation
*K*2	Constant of proportionality in exponential part of stream–aquifer flow equation
*K*3	Exponent in exponential part of the stream–aquifer flow equation
LOCATE	Parameter to fix the origin of the seasonal cycle of fluctuation of the parameters, COEFF, CRAK and SUB
MD	Exponent in depression flow equation
POWER	Routing exponent
SEAS	Parameter fixing the amplitude as a proportion of the mean in the seasonal fluctuation of the parameters, COEFF, CRAK and SUB
SMSC	Soil moisture store capacity
SQ	Exponent in infiltration capacity equation
SUB	Constant of proportionality in the calculation of interflow
VCOND	Constant of proportionality in the deep seepage equation

flow volumes estimated by MODHYDROLOG with different numbers of parameters optimized in the model calibrations, as well as the volumes estimated without model calibration (model parameters set to recommended values), are then compared to provide answers to the following questions.

(1) How 'physically based' is MODHYDROLOG? Can the model parameters be related to catchment physical and climatic characteristics? Must the model be calibrated for all applications?

(2) Is the use of all 19 model parameters necessary? How many model parameters must be optimized to obtain an adequate simulation of streamflow?

Although MODHYDROLOG has been used here, the results from this study would also have similar implications for other conceptual rainfall–runoff models. Based on the general results obtained from applying MODHYDROLOG to the 28 catchments, recommendations are also given in the Appendix to guide model users in optimizing and determining initial parameter values for MODHYDROLOG.



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. 1. Model structure of MODHYDROLOG.

2. MODHYDROLOG

The model structure of MODHYDROLOG and the equations representing the various hydrological processes are shown in Fig. 1 (model parameters are highlighted in bold in Fig. 1) and the 19 model parameters are listed in Table 1. A more complete description of MODHYDROLOG can be obtained from Chiew (1990) and Chiew and McMahon (1991), while Porter (1972) provides a detailed description of the origins of the equations used in MODHYDROLOG to represent the catchment hydrological processes.

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 moisture that infiltrates into the soil. Some of the water that cannot infiltrate is diverted to the depression store as regulated by the depression flow function while the remainder (surface runoff) flows to the stream. The depression store is subjected to consumptive demands from both evaporation and delayed infiltration to the soil moisture store.

All moisture that infiltrates is next subjected to a soil moisture function. This function diverts moisture to the stream as interflow and to the groundwater store as groundwater recharge. Moisture that is not diverted enters the soil moisture store. Evapotranspiration from the soil moisture store occurs at a rate that is dependent on potential evapotranspiration and the soil moisture status. 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 upwards movement of water from the underlying aquifers.

MODHYDROLOG takes into account spatial variation by allowing the user to apply the model individually to subareas within the one catchment (with different input data and parameter values). The outflow from each subarea becomes inflow into the next subarea, and together with the total runoff (sum of surface runoff, interflow and baseflow), is progressively routed to the catchment outlet using a non-linear routing technique. The spatial variability of rainfall (and irrigation or evapotranspiration) can therefore be easily accounted for. However, spatial variation is not allowed for in this study because model parameters are calibrated against streamflow records available only at the catchment outlet.

3. Optimization of 17 model parameters of MODHYDROLOG

MODHYDROLOG has 19 parameters. However, the parameter, LOCATE, can be set to 1 in the Southern Hemisphere to indicate that the cycle of parameter fluctuation starts in January (see Table 1). The parameter,

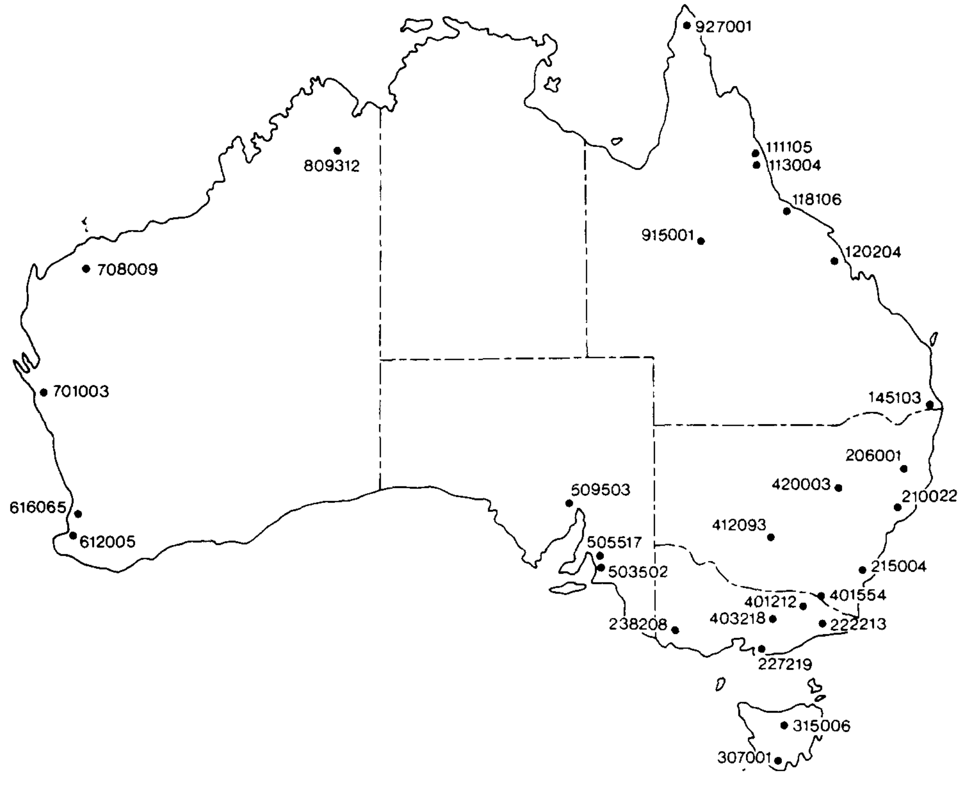


Fig. 2. Locations of catchments used for this study.

MD, governs the shape of the function whereby depression store fills. Although this flexibility has been programmed, there is virtually no information on how depression store fills, and Porter and McMahon (1976) recommend the use of $MD = 1$. This reduces the number of parameters in MODHYDROLOG to 17.

MODHYDROLOG (with 17 parameters) is applied to the 28 unregulated catchments (operated on a daily basis using daily rainfall and potential evapotranspiration data) listed in Table 2 (catchment locations are shown in Fig. 2). 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 catchments represent a large range of climatic and physical characteristics throughout Australia. The general information of the predominant catchment soil type listed in Table 2 is obtained only from the classification of Australian soils given by Northcote et al. (1975) while the information on the catchment cover is inferred directly from standard 1:100 000 maps published by the Australian Surveying and Land Information Group.

The model parameters for each of the 28 catchments, depending on the catchment characteristics, are set initially at the values recommended by Porter and McMahon (1976). The parameters are then optimized using a pattern search optimization procedure (see Hookes and Jeeves, 1961; Monro, 1971) to minimize the difference between the monthly simulated and recorded streamflow volumes given by the following objective function,

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

where SIM_i and REC_i are the simulated and recorded streamflows ($m^3\ s^{-1}$), respectively, of month i, and n is the number of months in the model simulation. In the model calibrations, lower and upper limits are set for each parameter (see Appendix) to ensure that the parameters take realistic values.

The calibration against monthly flows is adopted for this study because the routing of daily flows may be complicated by the different times used by the Australian authorities to record rainfall, climate and streamflow data. Rainfall and most climate observations are made at 09:00 h while daily streamflows are usually available on a midnight to midnight basis (see Chiew and McMahon, 1993a). This inconsistency in the time of measurement of data would, however, affect only the temporal distribution of daily runoff estimates and would have little effect on the monthly streamflow volumes. Nevertheless, although the model parameters are optimized to reproduce the monthly recorded streamflows, the results of parameter estimates from this study should also be applicable to model calibrations against runoff volumes over other time periods.

The entire period of available record listed in Table 2 is used for the model calibration to include as large a range of climatic characteristics as possible. The first year of model simulations is ignored to allow the model stores to achieve equilibrium levels. Although the correct procedure of model calibration and verification set out by Klemes (1986) is not followed, the model verifications carried out by Chiew and McMahon (1993a) and Chiew et al. (1993a) for nine of these catchments indicate that the optimized parameter values of MODHYDROLOG can reproduce the flow records of an independent test period.

The optimized parameter values are given in Table 3. The hydrographs in

Table 2
Summary of physical and climatic characteristics of the 28 unregulated catchments used for this study

Catchment	Period of record	Catchment area (km^2)	Altitude (m AHD)	Annual runoff[a] (ML) (mm)	C_v of runoff[b]	Annual rainfall[a] (mm) (season)	C_v of rainfall[b]	Soil type[c]	Catchment cover[d]
Queensland									
111105 Babinda Creek at The Boulders	1974–1989	39	50–1500	184000 (4700)	0.24	5400 (summer)	0.21	Clay	Forest
113004 Cochable Creek at Powerline	1974–1986	93	200–1200	193000 (2100)	0.45	2400 (summer)	0.24	Clay	Forest
118106 Alligator Creek at Allendale	1975–1989	69	10–1200	33000 (480)	0.59	1100 (summer)	0.34	Loam	Mixture
120204 Broken River at Crediton	1965–1979	41	750–1000	41000 (1000)	0.63	2100 (summer)	0.33	Duplex	Mixture
145103 Cainable Creek at Good Dam Site	1975–1987	41	150– 850	4300 (100)	1.02	900 (summer)	0.25	Duplex	Mixture
915001 Mitchell Grass at Richmond	1976–1988	3	200	50 (15)	1.68	450 (summer)	0.32	Clay	Grass
927001 Jardine River at Telegraph Line	1974–1989	2500	10– 150	2220000 (900)	0.31	1700 (summer)	0.19	Loam	Mixture
New South Wales									
206001 Styx River at Jeogla	1979–1986	163	1000–1600	74000 (450)	0.53	1300 (summer)	0.27	Duplex	Mixture
210022 Allyn River at Halton	1977–1984	205	250–1500	71000 (350)	0.74	1200 (summer)	0.32	Loam	Mixture
215004 Corang River at Hockeys	1980–1989	166	600– 900	55000 (330)	0.63	800 (uniform)	0.33	Duplex	Mixture
401554 Tooma River above Tooma Reservoir	1971–1979	114	1200–1800	158000 (1400)	0.36	1700 (uniform)	0.27	Loam	Forest
412093 Naradhan Creek at Naradhan	1978–1988	44	200– 500	80 (2)	1.88	450 (uniform)	0.33	Loam	Grass
420003 Belar Creek at Warkton	1973–1984	133	500–1200	14000 (110)	0.61	1100 (uniform)	0.30	Loam	Mixture
Victoria									
222213 Suggan Buggan River at Suggan Buggan	1972–1985	357	300–1800	55000 (150)	0.75	800 (uniform)	0.25	Duplex	Mixture
227219 Bass River at Loch	1974–1985	52	150– 300	17000 (330)	0.32	1100 (uniform)	0.12	Duplex	Grass
238208 Jimmy Creek at Jimmy Creek	1970–1989	23	400– 900	3700 (160)	0.47	650 (uniform)	0.18	Duplex	Forest
401212 Nariel Creek at Upper Nariel	1977–1987	252	500–1600	122000 (480)	0.42	1200 (winter)	0.24	Clay	Forest
403218 Dandongadale River at Matong North	1974–1984	182	300–1600	70000 (380)	0.70	1300 (winter)	0.33	Duplex	Forest

Tasmania									
307001 Davey River D/S Crossing River	1974–1990	686	200–1100	1390000 (2000)	0.13	2100 (winter)	0.10	Sand	Grass
315006 Forth River U/S Lemonthyme	1974–1985	311	300–1600	454000 (1500)	0.21	2000 (winter)	0.18	Loam	Forest
South Australia									
503502 Scott Creek at Scotts Bottom	1970–1985	27	200– 400	3600 (130)	0.60	950 (winter)	0.18	Duplex	Grass
505517 North Para River at Penrice	1978–1989	118	300– 500	6200 (50)	0.72	550 (winter)	0.19	Duplex	Mixture
509503 Kanyaka Creek at Old Kanyaka	1978–1989	180	200– 600	330 (2)	1.31	300 (winter)	0.32	Sand	Grass
Western Australia									
612005 Stones Brook at Mast View	1974–1984	15	150– 300	1800 (120)	0.71	1000 (winter)	0.15	Duplex	Forest
616065 Canning River at Glen Eagle	1977–1987	544	300– 400	8700 (20)	1.11	800 (winter)	0.16	Duplex	Forest
701003 Nokanena Brook at Wootachooka	1977–1986	229	100– 300	5000 (20)	0.81	400 (winter)	0.24	Duplex	Grass
708009 Kanjenjie Creek Tributary at Fish Pool	1974–1986	41	350	4100 (100)	1.06	400 (summer)	0.46	Duplex	Grass
809312 Fletcher Creek at Frog Hollow	1970–1980	30	400– 550	650 (20)	0.55	650 (summer)	0.32	Sand	Grass

[a] Mean annual runoff and rainfall are averaged over the period of record given in the second column.

[b] C_v is the coefficient of variation (standard deviation divided by the mean) of annual values over the period of record.

[c] Predominant soil type in catchment area is obtained from Northcote et al. (1975) with only four general classification (sand, loam, clay and duplex) used. Duplex soil has a sandy loam top layer and a clay subsoil.

[d] Three general classifications are used for catchment cover; grass (> 80% of catchment area is grass), forest (> 60% of catchment area is forest) and mixture (not 'grass' or 'forest').

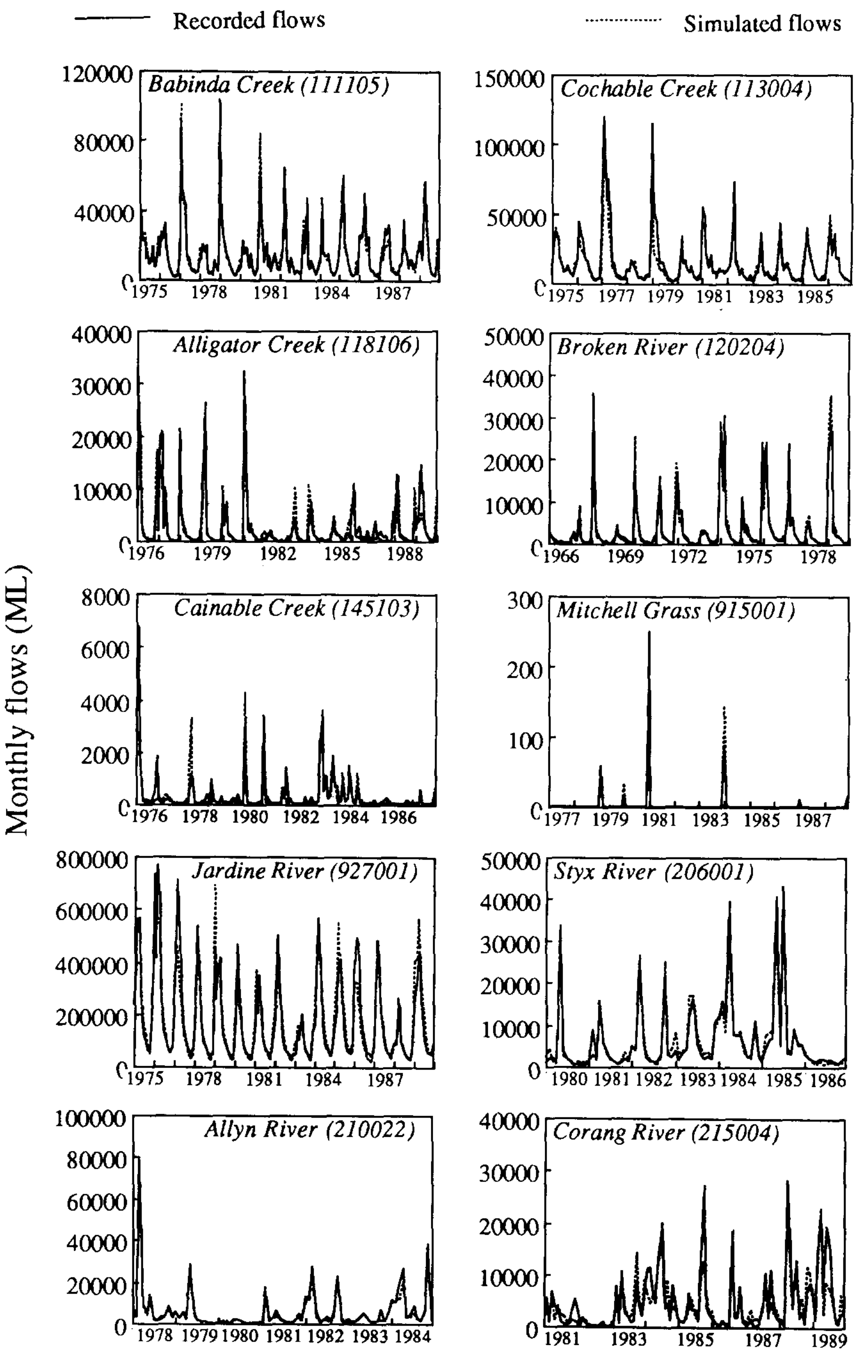


Fig. 3. Comparisons of monthly recorded streamflows and flows simulated by MODHYDROLOG for the 28 catchments.

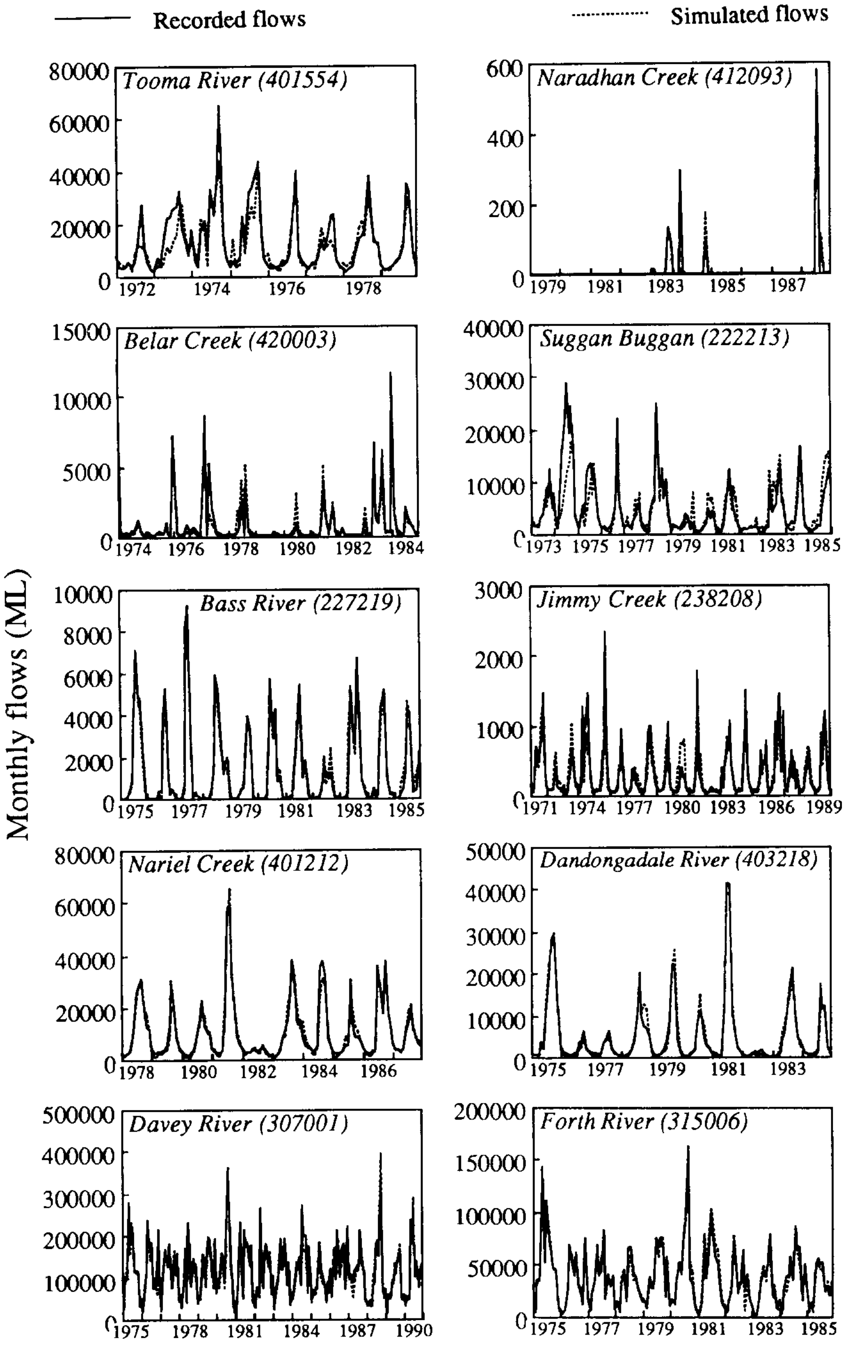


Fig. 3. Continued.

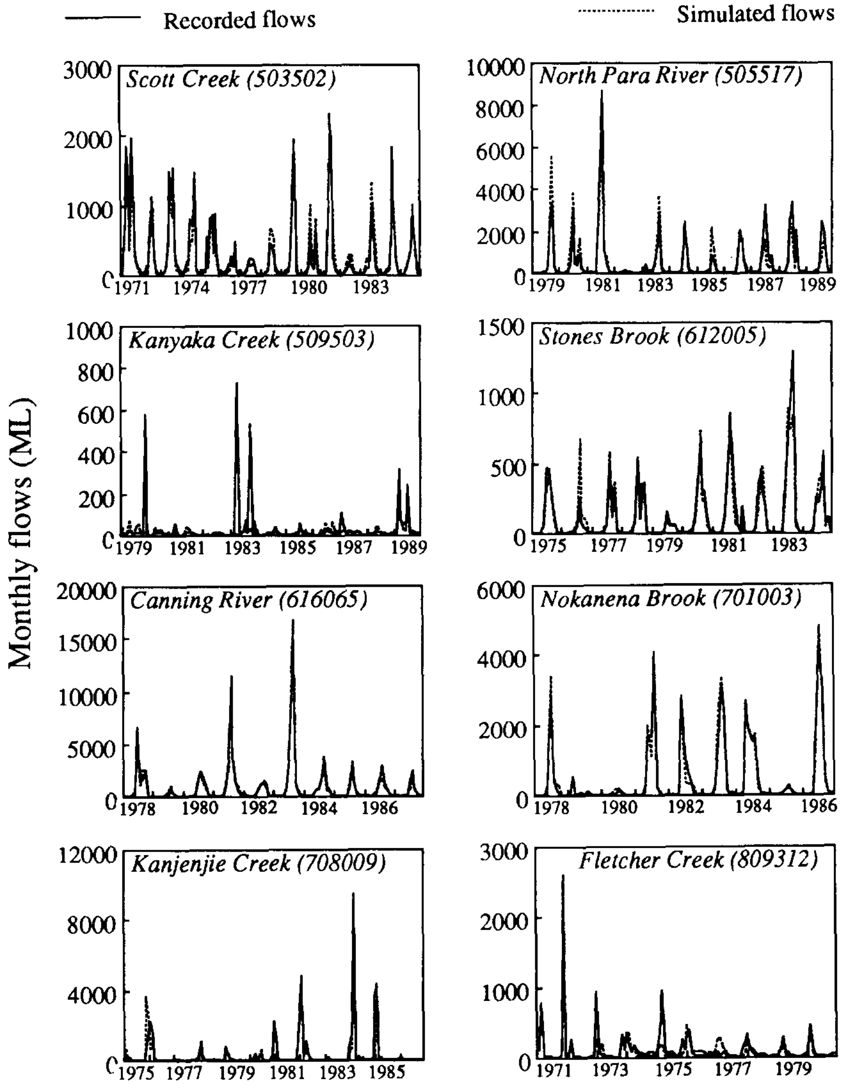


Fig. 3. Continued.

Fig. 3 show comparisons of the recorded monthly flows and the flows estimated by MODHYDROLOG. Although the hydrographs show little because of their condensed timescale, they are included to indicate the different flow characteristics of the various catchments. Table 4 tabulates the values of the objective function, the coefficient of efficiency and the ratio of total simulated to recorded flows. The coefficient of efficiency, E, in Table 4 is defined as

Table 3
Optimized parameter values

Catchment	INSC	COEFF	*SQ*	ADS	DSC	SUB	CRAK	SMSC	*EM*	SEAS	POWER	*CO*	*K*1	*K*2	*K*3	VCOND	DLEV
111105	*0.5*	295	**3.3**	XXX	XXX	0.42	**1.61**	*400*	*5.0*	XXX	*0.00*	*1.0*	0.030	0.010	10.0	XXX	XXX
113004	*0.5*	135	1.1	XXX	XXX	0.96	*2.00*	*400*	*5.0*	XXX	*0.00*	*1.0*	0.020	XXX	XXX	XXX	XXX
118106	*0.5*	385	**6.1**	0.5	*100*	XXX	1.00	*400*	5.2	XXX	*0.00*	*1.0*	0.018	XXX	XXX	0.007	−2.8
120204	*0.5*	**144**	**1.8**	0.2	31	0.07	0.23	310	6.0	XXX	*0.00*	*1.0*	**0.020**	XXX	XXX	XXX	XXX
145103	1.6	**140**	**3.3**	*1.0*	27	0.14	0.08	**155**	12.9	0.13	0.08	12.0	0.005	XXX	XXX	XXX	XXX
915001	4.2	**140**	**2.2**	XXX	XXX	XXX	XXX	**230**	13.5	XXX	*0.00*	5.0	XXX	XXX	XXX	XXX	XXX
927001	*0.5*	158	*0.0*	*1.0*	73	**0.41**	**0.96**	*400*	6.8	XXX	0.15	34.5	0.011	XXX	XXX	XXX	XXX
206001	0.8	263	**3.1**	XXX	XXX	0.30	**0.48**	**118**	22.0	XXX	*0.00*	20.0	0.020	XXX	XXX	XXX	XXX
210022	*0.5*	130	**2.2**	XXX	XXX	0.23	**0.26**	**240**	**8.5**	XXX	*0.00*	15.0	0.070	XXX	XXX	XXX	XXX
215004	*0.5*	190	**9.1**	0.6	40	0.29	0.82	175	12.5	XXX	0.25	*1.0*	0.040	XXX	XXX	XXX	XXX
401554	*0.5*	64	3.1	XXX	XXX	XXX	**2.00**	154	*5.0*	*1.00*	*0.00*	91.0	0.015	XXX	XXX	XXX	XXX
412093	**3.3**	**130**	**4.1**	*1.0*	16	XXX	XXX	**170**	**8.8**	XXX	**0.30**	**13.5**	XXX	XXX	XXX	XXX	XXX
420003	2.3	**120**	**1.1**	0.1	60	0.04	XXX	**170**	8.5	XXX	0.20	11.9	0.040	0.170	0.0	0.130	0.4
222213	*0.5*	195	1.0	*1.0*	36	0.28	1.14	140	21.5	0.65	0.23	11.0	0.018	0.050	11.0	0.049	0.4
227219	**1.3**	**140**	**3.1**	0.7	7	0.07	XXX	**125**	20.0	XXX	0.18	11.0	0.200	XXX	XXX	XXX	XXX
238208	0.9	120	4.6	0.3	24	0.09	0.82	155	9.0	0.50	0.30	20.0	0.080	0.030	5.0	0.030	1.6
401212	*0.5*	175	0.2	XXX	XXX	0.22	0.24	**331**	*5.0*	0.14	0.38	6.3	**0.032**	XXX	XXX	XXX	XXX
403218	**2.9**	**145**	**0.8**	*1.0*	18	**0.17**	**0.18**	**200**	**7.0**	XXX	**0.20**	**16.0**	**0.040**	XXX	XXX	**0.010**	0.6
307001	*0.5*	363	**7.6**	XXX	XXX	XXX	XXX	38	5.5	0.83	*0.00*	37.0	0.360	0.290	13.0	0.500	**3.9**
315006	*0.5*	65	4.1	0.2	33	0.61	1.63	65	9.5	0.60	0.10	12.0	0.080	0.130	7.0	XXX	XXX
503502	**1.9**	145	**2.6**	*1.0*	13	0.15	0.08	**160**	13.0	0.10	0.30	14.0	0.035	0.020	3.0	0.060	0.3
505517	**1.8**	**175**	**5.1**	*1.0*	19	0.07	0.42	**103**	16.0	0.60	0.10	34.0	0.020	XXX	XXX	**0.040**	0.0
509503	1.2	255	*0.0*	XXX	XXX	0.03	0.94	355	5.5	XXX	*0.00*	20.0	XXX	XXX	XXX	0.220	0.0
612005	**3.9**	130	1.2	*1.0*	10	XXX	0.16	**230**	13.5	0.30	0.40	12.0	**0.060**	0.060	0.0	**0.070**	0.0
616065	**5.6**	185	*0.0*	*1.0*	19	0.04	**0.18**	**260**	24.5	**0.85**	0.10	34.0	**0.040**	XXX	XXX	**0.070**	0.0
701003	**2.7**	**145**	**3.8**	*1.0*	40	XXX	0.08	**150**	6.9	0.48	**0.10**	**24.5**	0.020	0.040	5.0	XXX	XXX
708009	4.3	330	6.2	0.8	*100*	*1.00*	0.58	**225**	7.5	XXX	*0.00*	*1.0*	0.540	0.130	4.0	XXX	XXX
809312	2.7	**145**	1.6	*1.0*	*1*	0.17	1.92	65	16.5	0.40	*0.00*	5.0	XXX	0.030	1.0	0.030	0.1

Value in bold indicates that objective function is sensitive (SEN > 0.5 for < 50% change of parameter about its optimal value — see Section on Analysis of model parameters) to the parameter value.
Value in italic indicates that optimized parameter value is at the upper or lower limit.
XXX indicates that parameter is at inoperative value (i.e. the process it represents is not occurring in the catchment).

Table 4
Values of objective function, coefficient of efficiency and ratio of total simulated to total recorded flows for the 28 catchments

Catchment number	Number of months simulated	Value of objective function ($m^3 s^{-1}$)	Coefficient of efficiency (E)	Ratio of total simulated to total flows
111105	180	362	0.93	0.97
113004	144	874	0.80	0.87
118106	168	477	0.82	0.94
120204	168	102	0.97	1.01
145103	144	49.2	0.84	0.95
915001	144	0.45	0.92	0.97
927001	180	7340	0.84	0.99
206001	84	120	0.95	0.98
210022	84	131	0.97	0.93
215004	108	368	0.77	0.89
401554	96	466	0.79	0.88
412093	120	2.97	0.92	0.84
420003	132	93.9	0.89	0.93
222213	156	517	0.71	0.94
227219	132	43.0	0.96	0.96
238208	228	40.1	0.75	0.97
401212	120	191	0.94	0.99
403218	120	130	0.96	1.00
307001	192	1550	0.93	0.98
315006	132	511	0.94	0.99
503502	180	20.1	0.93	0.98
505517	132	57.3	0.81	0.97
509503	132	21.4	0.07	0.51
612005	120	7.39	0.86	0.97
616065	120	30.6	0.97	0.97
701003	108	24.2	0.95	0.98
708009	144	85.6	0.78	0.83
809312	120	24.7	0.68	0.79

$$E = \frac{\sum_{i=1}^{n}(\mathrm{REC}_i - \overline{\mathrm{REC}})^2 - \sum_{i=1}^{n}(\mathrm{SIM}_i - \mathrm{REC}_i)^2)}{\sum_{i=1}^{n}(\mathrm{REC}_i - \overline{\mathrm{REC}})^2} \qquad (2)$$

where $\overline{\mathrm{REC}}$ is the mean monthly recorded flow. The coefficient of efficiency expresses the proportion of the variance of the recorded flows that can be accounted for by the model (Nash and Sutcliffe, 1970) and provides a direct measure of the ability of the model to reproduce the recorded flows with E =

1.0 indicating that all the simulated flows are the same as the recorded flows.

MODHYDROLOG could not reproduce the long periods of zero flows with sudden peaks in the hydrographs of the Kanyaka Creek catchment (509503) (and to a lesser extent, the Fletcher Creek catchment (809312)). The poor simulation in the Kanyaka Creek catchment is also indicated by the low value of E and the total simulated flow being only 50% of the total recorded flow. However, the hydrographs in Fig. 3 suggest that the flow simulations for the other catchments (including two other catchments with 'peaky' hydrographs — Mitchell Grass (915001) and Naradhan Creek (412093)) are satisfactory.

The coefficient of efficiency is always greater than 0.7 (except for the Kanyaka Creek catchment) and is greater than 0.8 in 21 of the 28 catchments. A survey carried out by the authors to assess the quality of catchment streamflow yield estimates (Chiew and McMahon, 1993b) indicates that simulations with $E = 0.6$ are generally considered to be satisfactory and simulations with $E = 0.8$ are always considered to be acceptable for typical hydrological studies. The total simulated flow volumes are also generally within 15% of the total recorded flow volumes and are within 5% in 17 of the simulations (Table 4). In a 'flow estimate survey' conducted by the authors (see discussion on Table 6), almost all 63 participants assessed the flow simulations in 26 of the 28 catchments to be acceptable for use in catchment yield studies. As such, except for the Kanyaka Creek catchment, the simulations are considered to be satisfactory for the purpose of this study.

The choice of an appropriate criterion to assess the simulations should depend on the intended application of the flow estimates. The objective function given by Eq. (1) is arbitrarily chosen to provide a satisfactory measure of the quality of the simulation of both high and low flows. The optimization of model parameters to minimize the value of this objective function does not necessarily (although they generally do) lead to a high value of E or a good agreement between the total simulated and recorded flows. In a separate study by the authors on the 28 catchments (Chiew et al., 1993b) where model parameters are optimized to minimize the value of the same objective function but at the same time ensuring that the volume of total simulated flow is within 5% of the total recorded flow, all simulations (except for the Kanyaka Creek catchment) led to a value of E greater than 0.8. This, and results from other studies, indicates that MODHYDROLOG generally gives satisfactory estimates of monthly flows although more care must be given to the optimization of model parameters in the drier catchments with ephemeral streams.

4. Analysis of model parameters

The relative importance of the model parameters is analysed by altering each parameter (by −80 to +100%, in steps of 10%) about its optimized value (while other parameters are kept at their optimized values) and calculating a measure of the sensitivity of the objective function to the change in the parameter value. The sensitivity measure used here is defined as the ratio of proportionate change in the value of the objective function resulting from the change in the parameter value

$$\mathrm{SEN} = 100\frac{\mathrm{NEW} - \mathrm{OLD}}{\mathrm{OLD}|PC|} \tag{3}$$

where SEN is the sensitivity measure of the objective function resulting from the change in parameter value, NEW is the new value of the objective function resulting from the new parameter value, OLD is the original value of the objective function (as in Table 4) and $|PC|$ is the absolute percentage change in parameter value. A value of SEN = 1.0 means that a 1% change in the parameter value (about the value under consideration) would result in a 1% change in the value of the objective function.

It is not the intention of this study to perform a detailed sensitivity investigation where the parameter derivatives and response surface of the objective function can be analysed to furnish information on parameter means and standard deviations and cross-correlations between parameters (see Kuczera, 1983; Chiew and McMahon, 1990). For the purpose of this study, the simple measure described by Eq. (3) is sufficient to provide guidance on the relative importance of the model parameters. For example, a large SEN value would indicate that a small change in the parameter value can affect significantly the value of the objective function, and the parameter must be optimized adequately. A very small SEN value indicates that the parameter is of little importance and can take almost any value without affecting significantly the streamflow estimates.

The analysis is carried out for all model parameters (except when a parameter takes an inoperative value) in all 28 catchments. The parameters are highlighted in bold in Table 3 whenever a change of less than 50% about their optimized values results in SEN being greater than 0.5. These parameters are referred to as 'important' in the following discussion. Although Table 3 indicates that the parameters can take a large range of values, the objective function is rarely sensitive to the parameters at 'extreme' values, with the 'important' parameters generally falling in a smaller range of values. Based on the analysis, the importance of the 17 parameters is discussed below. Whenever the parameter estimates can be related to some catchment characteristics (based on this study and the values recommended by Porter and McMahon (1976)), the relationship is given in the Appendix. The coefficients of determination, R^2, given throughout this section are for correlations between the optimized parameter values and the values that the parameters should take based on the catchment characteristics. The correlations are not statistically significant (at the 5% level) for almost all the parameters. The parameter values reported throughout this paper assume the use of SI units (where daily rainfall and potential evapotranspiration input data are in millimetres).

4.1. Interception (INSC)

The optimized value of the interception capacity, INSC, is at its lower limit of 0.5 for 12 catchments. Eleven of these catchments have a runoff coefficient (streamflow divided by rainfall) greater than 0.3. In fact, 11 of the 12 catchments (of the 28 considered for this study) with runoff coefficients greater than 0.3 have INSC optimized at 0.5, with the other catchment (206001) also having a low optimized INSC value of 0.8. At these catchments, SEN for changes in the value of INSC is extremely small (<0.05). The parameter, INSC, is optimized at its lower limit in these catchments because MOD-HYDROLOG is attempting to allow as much of the rainfall as possible to pass through the interception store. It thus appears that INSC can be set to 0.5 in catchments where the runoff coefficient is greater than 0.3. The lower limit of 0.5 is used to allow for some realistic simulation of interception. In any case, the use of a value lower than 0.5 would not improve the overall simulation of runoff significantly as indicated by the low values of SEN.

At the remaining catchments, SEN is generally high for changes in optimized INSC values, indicating that INSC should be optimized for most catchments. Eight of the INSC values are 'important' (see Table 3) and there is a correlation of $R^2 = 0.35$ ($R^2 = 0.65$ ignoring the Canning River catchment) between these eight INSC values and the three classifications used to describe the catchment cover (see Table 2).

4.2. Infiltration capacity (COEFF, SQ)

The sensitivity measure, SEN, is generally high for changes in the values of the parameters in the infiltration capacity equation, COEFF and SQ, indicating that it is necessary to use these two parameters in all catchments. Although the optimized COEFF values range from 64 to 385, the ten 'important' COEFF values take a much smaller range (120–175). There is a correlation of $R^2 = 0.3$ between the ten 'important' COEFF values and the four classifications used to describe the predominant catchment soil type (see Table 2), and the relationship given in the Appendix can be used for choosing an appropriate initial value of COEFF. The parameter, *SQ*, is also extremely important, with the *SQ* values in Table 3 being highlighted in bold in 16 of the 28 catchments. However, it is difficult to relate *SQ* to any catchment characteristic. The estimation of *SQ* is further complicated by the fact that it can take a very large range of values (0.0–9.1 for the 28 catchments). A value of 3 (average of the 28 optimized values) may be used as an initial estimate, but *SQ* must be optimized for all model simulations.

As the two parameters appear in the same equation, they are highly correlated (see also Chiew and McMahon, 1990; Wong and Mustinov, 1987), and changes in one parameter value can usually compensate for changes in another parameter value. The importance of COEFF and *SQ* should be sufficient to justify their inclusion in all parameter optimization runs. However, because of their high intercorrelation, in applications where only approximate runoff estimates are required, the user may wish to set COEFF to a value depending on the predominant soil type (see Appendix) and optimize *SQ* only.

4.3. Depression flow (ADS, DSC)

The simulation of depression flow is not required in nine catchments where ADS is optimized at the inoperative value of zero. The value of SEN for changes in the values of ADS and DSC for the remaining 19 catchments is always smaller than 0.03, indicating that the depression flow parameters have little effect on the objective function. The depression flow component is also usually very small, and although the use of ADS and DSC may provide a small improvement to daily flow estimates, the depression flow component has practically no effect on the estimation of runoff volumes over longer time periods (more than 1 day). For this reason, the representation of depression flow is not necessary and ADS can be set to zero.

4.4. Interflow (SUB)

The simulation of interflow is not required in seven catchments and the interflow parameter, SUB, is 'important' in only two catchments. However, interflow can be a significant component of runoff, with approximately 20% of the total runoff contribution in all 28 catchments coming from interflow. Although true interflow is likely to occur where soils have contrasting profile (duplex soil), SUB may also be used to represent partial area contribution where soils near the river are less permeable than predominant soil types in the catchment. Interflow can also occur in mountain forest soils where vegetation activity can create a surface layer of much greater porosity. The interflow parameter, SUB, should be optimized because it is difficult to predict whether interflow is occurring in a catchment. However, where only approximate runoff estimates are required, interflow need not be simulated and SUB can be set to zero. In most cases, satisfactory estimates of streamflow can still be obtained, even in catchments where interflow may occur, as the other parameter values can be optimized so as to give greater contributions from other runoff components (surface runoff and baseflow).

It is difficult to relate SUB to any catchment characteristic although the Appendix gives some guidance on estimating SUB for the different soil types. The values in the Appendix are obtained by averaging the optimized SUB values for all catchments with the particular soil type. The correlation is extremely poor ($R^2 = 0.1$).

4.5. Groundwater recharge (CRAK)

Although recharge does not occur in five of the catchments, SEN is generally high for changes in optimized CRAK values in the other catchments. The simulation of recharge is important in MODHYDROLOG because it is related to the estimation of other hydrological fluxes. It determines the amount of infiltrated water that enters the groundwater store, which can then become runoff (as baseflow) or lost to the catchment through deep seepage. On the other hand, infiltrated moisture that does not become recharge flows into the soil moisture store, most of which is eventually lost through evapotranspiration. For this reason, CRAK should be optimized in all model simulations. Although CRAK can take a large range of values (0.0–2.0), there is a correlation of $R^2 = 0.45$ (for the seven 'important' CRAK values) between CRAK and the predominant soil type (and average catchment rainfall).

4.6. Soil moisture store capacity (SMSC)

The soil moisture store capacity, SMSC, is an important parameter as it is used in the simulation of many processes (infiltration, interflow, groundwater recharge, infiltration and evapotranspiration). The sensitivity measure, SEN, is high for changes in optimized SMSC values, with SMSC being 'important' in 15 catchments. For this reason, SMSC must be optimized in all applications. Its value can range from 40 to 400 and there is a correlation of $R^2 = 0.4$ (for the 15 'important' SMSC values) between SMSC and the predominant soil type (and catchment cover).

4.7. *Evapotranspiration* (EM)

The parameter, *EM*, represents the maximum plant-controlled rate of transpiration and should not exceed 13 mm for common vegetation. Although the optimized *EM* values exceed 13 mm in eight catchments, SEN is smaller than 0.2 in these catchments. There is a correlation of $R^2 = 0.85$ (with only the three 'important' *EM* values considered) between *EM* and the catchment cover. The range of *EM* values is also small, and in most applications, it is sufficient to set *EM* to the values given in the Appendix.

4.8. *Seasonal fluctuation (SEAS)*

The use of SEAS is not required in 15 catchments, and except for the Canning River catchment (616065), SEN in other catchments where SEAS is applicable is extremely small (< 0.05). The parameter, SEAS, allows for the fluctuations in the values of the parameters, COEFF, SUB and CRAK, through the year. It is included in MODHYDROLOG as it may improve the simulation of runoff in arid catchments where, as a result of extreme desiccation during long hot summers, physical changes can be wrought on catchment features (hence the need to use different parameter values). In non-arid catchments, seasonal fluctuation in parameter values is not required, and SEAS can be set to zero.

4.9. *Runoff routing (*CO, *POWER)*

The exponent, POWER, allows for non-linear storage in the routing of runoff to the catchment outlet. The optimized value of POWER is zero in 12 catchments, indicating that a linear storage in routing has been adopted. Where POWER takes non-zero values, it is 'important' in only three catchments, and in all other catchments, SEN is always smaller than 0.1 for changes in optimized POWER values. The other routing parameter, *CO*, is also 'important' in the same three catchments where POWER is 'important'. The two parameters appear in the same equation and are highly correlated, and for this reason, POWER can be set to zero to reduce the number of model parameters, and *CO* can be optimized where necessary. Although *CO* can take a large range of values, SEN for the 'extreme' values is practically zero. There is a correlation of $R^2 = 0.95$ (considering the five cases where SEN for *CO* exceeds 0.2) between *CO* and catchment physical characteristics (stream length and catchment slope — see Appendix).

The two routing parameters are not important in this study because only the monthly flow estimates are considered. The routing parameters can be set to the values given in the Appendix for flow simulations over long time periods (more than 1 week). However, the parameters affect the temporal estimation of runoff on a daily basis, and *CO* should be optimized if flow estimates over a short time period (for example, daily) is required.

4.10. *Baseflow (K1, K2, K3)*

The parameter, *K*1, governs the linear part of the baseflow equation while the parameters, *K*2 and *K*3, determine the baseflow contribution from the exponential part. Although baseflow in practically zero in the drier catchments (annual rainfall less than 500 mm), the baseflow component of runoff is generally greater than 50% in the wetter catchments. For this reason, an accurate determination of baseflow is essential in obtaining reliable estimates of runoff. Nevertheless, the exponential part of the baseflow equation is used in only 11 catchments, and in all these catchments, SEN values for changes in optimized *K*2 and *K*3 values are always smaller than 0.05. The use of a single parameter, *K*1 (*K*2 can be set to zero), to represent baseflow should thus be sufficient in most applications. However, it is difficult to relate *K*1 to any catchment characteristic. A value of 0.04 (average of the five 'important' *K*1 values) may be used as an initial estimate, but *K*1 should be optimized in all simulations where annual catchment rainfall exceeds 500 mm.

4.11. *Deep seepage (VCOND, DLEV)*

Although the simulation of deep seepage is required for only 12 of the 28 catchments, deep seepage can represent a significant portion of rainfall water lost to the catchment. On average, approximately 5% of rainfall water is lost to deep seepage in the remaining catchments and this can reach up to 20% in some catchments. The simulation of deep seepage is thus necessary in MOD-HYDROLOG.

The parameter, DLEV, is optimized at non-zero values in only eight catchments, and except for the Davey River catchment (307001), SEN for changes in optimized DLEV values is zero in most cases. The parameter, DLEV, is 'important' for the Davey River catchment as upwards movement of water from the deeper aquifer (or water outside the catchment boundary) into the groundwater store is simulated here to satisfy the high runoff coefficient (95%) in the catchment. As the two parameters, DLEV and VCOND, appear in the same equation and are highly correlated, it is unnecessary to optimize both parameters. The parameter, DLEV, can be set to −0.1 (to allow for the simulation of river recharge, see Chiew and McMahon (1991)), with only the parameter VCOND optimized in the model calibration. It is difficult to determine an appropriate value for VCOND, and the inoperative value of zero may be used as the initial estimate.

5. Comparison of runoff volumes estimated with different numbers of model parameters optimized

The discussion in the previous section indicates that some parameters are more important than others, and the use of all the model parameters in MODHYDROLOG is not necessary. The optimization of fewer model parameters may be sufficient to give similar flow estimates compared with the estimates obtained using all the model parameters. In this section, MODHYDROLOG is re-calibrated for the 28 catchments, with fewer parameters optimized in the model calibration. As in the model calibrations described earlier, the parameters considered for the model calibration are initially set to the recommended values and optimized (using the pattern search procedure) to minimize the square root objective function described by Eq. (1). The following four cases (in decreasing numbers of parameters optimized) are compared. (1) All 17 parameters optimized (as in the earlier section). (2) Nine parameters optimized (INSC, COEFF, *SQ*, SUB, CRAK, SMSC, *EM*,*K*1, VCOND). All parameters which are 'important' in more than one catchment (see Table 3 and earlier discussion) are included. The parameter, *CO*, is set to the value recommended in the Appendix and POWER is set to zero to allow a linear storage in runoff routing. The parameter, DLEV, is set at −0.1. Depression flow is not simulated (ADS and DSC are set to zero), seasonal fluctuations in parameter values are not allowed for (SEAS set to zero) and the exponential term in the baseflow equation is not used (*K*2 and *K*3 are set to zero). (3) Four parameters optimized (*SQ*, CRAK, SMSC, *K*1). The objective function is very sensitive to these four parameters and it is difficult to provide reasonable estimates for these parameters based on the catchment characteristics. The parameter, COEFF, is set to the recommended value given in the Appendix because there is a fair correlation between COEFF and the predominant catchment soil type, and a poor estimate of COEFF can usually be compensated for by the other infiltration parameter(*SQ*) to which it is highly correlated. The loss parameters, INSC and *EM*, are not extremely important and can be related to the catchment cover, and they are set to the values recommended in the Appendix. The interflow (SUB set to zero) and deep seepage (VCOND and DLEV set to zero) processes are not simulated. As in the second case, the parameters, ADS, DSC, SEAS, *K*2 and *K*3, are all set to zero. (4) No optimization. Nine parameters (INSC, COEFF, *SQ*, SUB, CRAK, SMSC, *EM*, *CO*, *K*1) are set to the values

Table 5
Values of objective function for four cases of model simulations with different numbers of model parameters optimized

Catchment Number	Values of objective functions ($m^3 s^{-1}$) for model calibrations where the following numbers of parameters are optimized			
	17	9	4	0
111105	**362**	**397**	*432*	1270
113004	**874**	**893**	*1000*	2740
118106	**477**	**505**	*571*	772
120204	**102**	**111**	*114*	507
145103	**49.2**	**52.4**	*61.0*	123
915001	**0.449**	**0.449**	**0.480**	12.8
927001	**7340**	**7810**	12000	65800
206001	**120**	**120**	*170*	353
210022	**131**	**131**	**132**	274
215004	**368**	**368**	**383**	*492*
401554	**466**	746	746	853
412093	**2.97**	9.26	10.3	82.0
420003	**93.9**	*121*	260	1890
222213	**517**	**524**	1060	1970
227219	**43.0**	*54.5*	*54.5*	185
238208	**40.1**	50.5	70.9	203
401212	**191**	296	296	1730
403218	**130**	*162*	254	850
307001	**1550**	3800	4780	10810
315006	**511**	**564**	*618*	1070
503502	**20.1**	**22.2**	41.7	138
505517	**57.3**	*76.9*	91.4	124
509503	**21.4**	**21.4**	40.2	203
612005	**7.39**	13.9	35.6	178
616065	**30.6**	49.5	346	5310
701003	**24.2**	44.9	50.0	135
708009	**85.6**	*102*	*112*	168
809312	**24.7**	39.3	56.1	231

The value of the objective function is highlighted in bold whenever it is less than 10% greater than the value of the objective function for model optimization using all 17 parameters and indicated in italic when it is between 10 and 50 greater.

recommended in the Appendix and all the remaining parameters are set to inoperative values.

The values of the objective function for these four cases are given in Table 5. The 112 flow simulations (four in each of the 28 catchments) are also used in a related study where 90 people (of which 63 responded) throughout Australia working in the field of hydrology and water resources are invited to assess the

Table 6
Categories used by the most number of participants in a 'flow estimates survey' to classify the flow estimates simulated with different numbers of parameters used in the optimization of MODHYDROLOG

Catchment Number	Categories selected for model optimization with			
	17 parameters	9 parameters	4 parameters	0 parameters
111105	1	1	1	2
113004	2	3	3	3
118106	2	2	2	2
120204	1	1	1	2
145103	2	2	2	3
915001	2	2	2	4
927001	2	2	2	3
206001	1	1	2	2
210022	1	1	1	2
215004	2	2	2	3
401554	2	3	3	3
412093	2	4	4	4
420003	2	2	3	4
222213	2	3	3	4
227219	1	1	1	2
238208	2	3	3	4
401212	1	1	1	3
403218	1	1	2	3
307001	1	2	2	3
315006	1	1	1	1
503502	1	1	2	4
505517	2	2	3	3
509503	4	4	4	4
612005	2	2	4	4
616065	1	1	4	4
701003	1	3	3	3
708009	2	3	3	3
809312	3	4	4	4

The numbers refer to the following categories: 1, ACCEPTABLE — perfectly acceptable result; 2, ACCEPTABLE — use with reservation, 3, UNACCEPTABLE — use only if there is no other alternative; 4, UNACCEPTABLE — never use under any condition.

quality of the monthly streamflow estimates. Hydrographs and X–Y plots showing comparisons of the 112 simulated and recorded flows, as well as several statistical measures of the flow comparisons (coefficient of determination, coefficient of efficiency, equation of line of best fit between simulated and recorded flows and ratio of total simulated and recorded flows) are given to the participants, and they are asked to classify the flow estimates into one of these four categories: 'perfectly acceptable result', 'acceptable but use with reservation', 'use only if there is no other alternative' or 'never use under any condition'. This study is described in detail in Chiew and McMahon (1993b) while Table 6 tabulates the category selected by the most number of participants for the 112 simulations.

Table 6 indicates that most participants categorized the monthly flows estimated when nine parameters are optimized to be as good as those estimated using 17 parameters in approximately 70% of the catchments considered for this study. The monthly flows estimated from the optimization of nine parameters for 19 of the 28 catchments (compared with 26 when 17 parameters are optimized) are considered by the participants to be acceptable for use in typical hydrology and water resources studies. The quality of the monthly flows estimated when four parameters are optimized is considered to be the same as those estimated using 17 parameters in about 50% of the catchments, with flow estimates for 15 of the 28 catchments still considered to be acceptable for typical applications. However, the participants assessed that the streamflow volumes estimated without any model calibration are significantly poorer than the estimates obtained through model calibration, with only the simulations at seven of the 28 catchments considered to be acceptable.

In general, it appears that the values of the objective function chosen for this study (Eq. (1)) must differ by more than 50% before a different category is used to classify the quality of the flow estimates. Nevertheless, although the 'flow estimates survey' provides a useful indication on the quality of the flow simulations, the estimates obtained with different numbers of parameters optimized in the model calibration, are best assessed by comparing the values of the objective function tabulated in Table 5. This is because the model parameters have been optimized to minimize the value of the objective function (and not some other criterion).

The values of the objective function when nine parameters are optimized (see Table 5) are within 10% of the values of the objective function when 17 parameters are optimized in 50% of the catchments (includes all the seven catchments in Queensland), and within 50% in 20 of the 28 catchments. The values of the objective function differ by more than 200% in only two catchments. The plots in Fig. 4 show comparisons of monthly recorded streamflows and the monthly flows simulated when 17 and nine parameters are optimized for the two catchments. The plots indicate that the quality of flow simulations for the Davey River catchment (307001) are almost the same, while the flows estimated using 17 parameters for the Naradhan Creek catchment (412093) are better than those estimated when only nine parameters are optimized. However, Naradhan Creek is ephemeral and dry for most parts of the year,

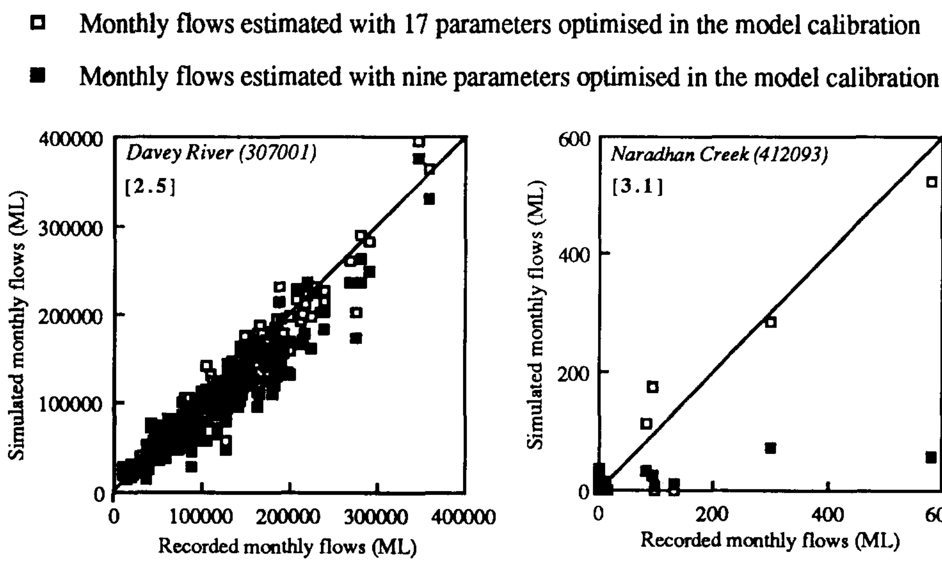


Fig. 4. Comparisons of monthly recorded flows and the flows simulated with 17 and nine parameters optimized in the only two catchments where the values of the objective functions differ by more than 200% ([2.5] indicates that the value of the objective function when nine parameters are optimized is 2.5 times the value of the objective function when 17 parameters are optimized).

and this assessment is based on only two occasions (see Fig. 4) when high flows are recorded. This study thus indicates that although the flows estimated when all the model parameters are optimized are better than those estimated with fewer model parameters optimized, the flows estimated with the optimization of nine parameters are comparable with those estimated using 17 model parameters.

The values of the objective function for model calibrations when four parameters are optimized are within 10% of those obtained when 17 parameters are optimized in only three catchments, and within 50% in 12 catchments. The values for model calibrations using four parameters are more than twice those obtained using 17 parameters in nine of the 28 catchments. The plots in Fig. 5 show comparisons of recorded monthly and simulated flows for one typical catchment where the value of the objective function when four parameters are optimized is only slightly more than two times that when 17 parameters are optimized (four of the nine cases) and for the remaining five catchments.

Compared with the simulations when 17 and nine parameters are optimized, the interflow and deep seepage processes are not simulated when only four model parameters are optimized. The simulation of interflow may not be essential because interflow can usually be compensated for by larger contributions from other runoff components. However, the deep seepage

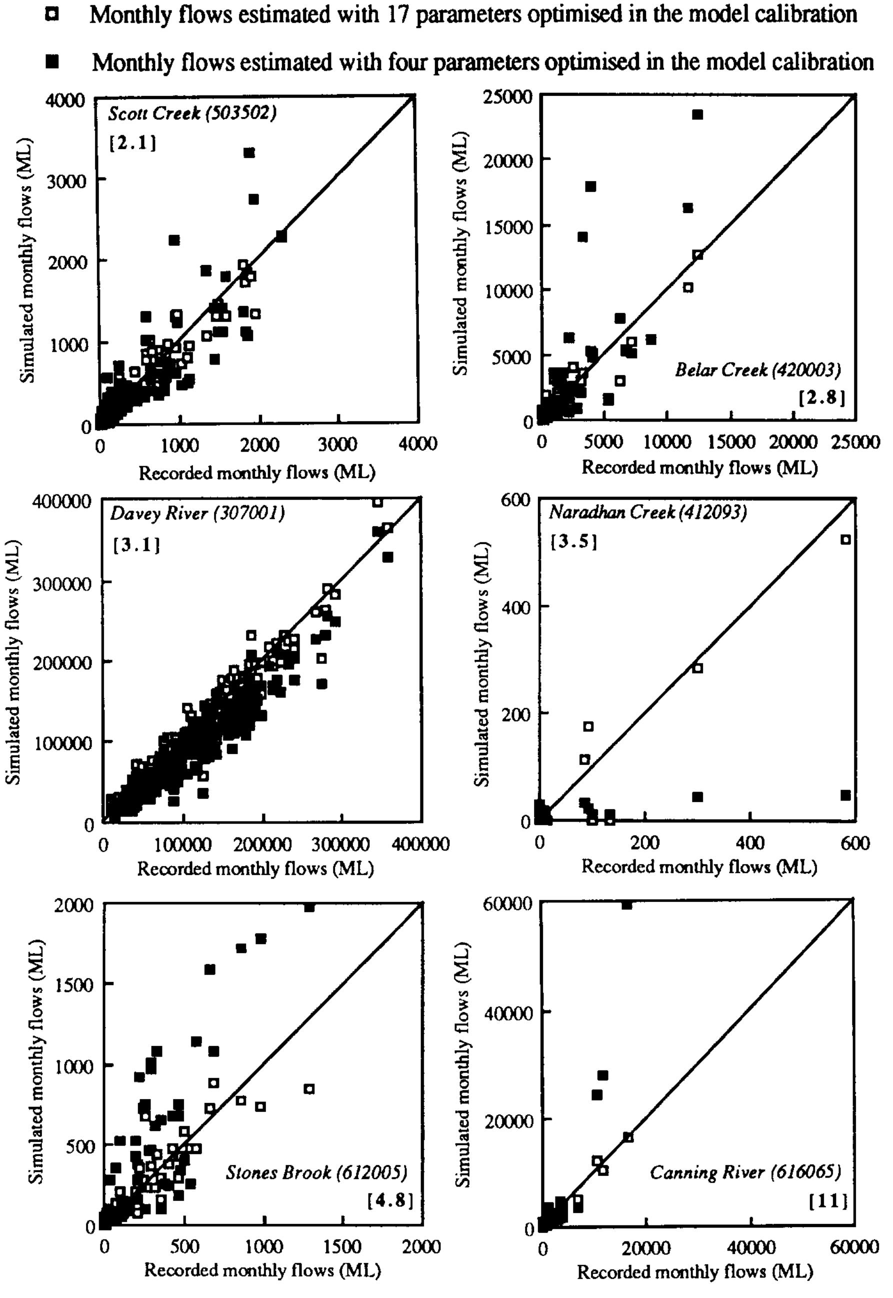


Fig. 5. Comparisons of monthly recorded flows and the flows simulated with 17 and four parameters optimized in one typical catchment where the value of the objective function when four parameters are optimized is only slightly more than twice the value of the objective function when 17 parameters are optimized (one of four cases) and in the remaining five catchments where values of the objective function when four parameters are optimized are more than twice the values when 17 parameters are optimized.

represents water lost to the catchment, and an adequate simulation of deep seepage is usually required in catchments where runoff coefficients are low (where a large proportion of rainfall water may be lost to the catchment through deep seepage). This partly explains why the flow estimates obtained when only four model parameters are optimized are comparable with the flow estimates obtained when more parameters are optimized in the Queensland catchments and other catchments with a temperate climate (where the runoff coefficient is generally high). Table 3 also indicates that the deep seepage parameter, VCOND, is optimized at an inoperative value of zero in these catchments. However, the flow estimates obtained with four parameters optimized are usually poorer than those obtained when 17 or nine parameters are optimized in the dry catchments with low runoff coefficients (< 0.1). In any case, it is almost always more difficult to simulate runoff in semiarid and arid catchments compared with wetter catchments. This is because the processes governing the relationship between rainfall and runoff in arid catchments, where runoff is a small proportion of rainfall and where streams are ephemeral, are more complicated than in wet catchments.

The monthly flows estimated by MODHYDROLOG without any model calibration (parameters are set at the recommended values depending on catchment physical and climatic characteristics) are considerably less satisfactory than the flows estimated when a model calibration is performed. The values of the objective function when no model calibration is carried out are more than five times the values of the objective function when 17 parameters are optimized in 50% of the catchments considered for this study. In five of the 28 catchments, the values of the objective function with no model calibration are more than an order of magnitude greater than the values when 17 parameters are optimized. Although MODHYDROLOG is purported to be 'physically based' and certain parameters can be related to the catchment characteristics, it is difficult to determine the values of some of the important parameters, and for this reason, MODHYDROLOG should always be calibrated against streamflow data in all modelling applications.

6. Conclusions

This paper describes the application of a daily rainfall–runoff model, MODHYDROLOG, to 28 catchments throughout Australia with different climatic and physical characteristics. Four simulations are carried out for each catchment, with the simulations differing in the numbers of model parameters optimized in the model calibration. Comparisons of monthly simulated and recorded streamflows indicate that MODHYDROLOG generally gives satisfactory estimates of runoff, although it has some difficulty in simulating long periods of zero flows followed by peaks in the hydrographs of ephemeral streams in arid catchments.

The sensitivity analysis indicates that some model parameters are more important than others and the optimization of all 19 model parameters is not necessary. The model calibrations in the previous section indicate that the optimization of nine (or fewer) parameters is sufficient to give adequate estimates of streamflow for most applications. The use of four or five parameters may be sufficient in temperate catchments and in applications where only approximate estimates of runoff are required.

MODHYDROLOG is purported to be 'physically based' and the investigation of the model parameters indicates that certain parameters can be related to the catchment characteristics. However, it is difficult to estimate the values of some of the 'important' parameters, and for this reason, MODHYDROLOG should always be calibrated in all modelling applications. Based on the general results from this study, recommendations are given in the Appendix to guide model users in optimizing and determining initial parameter values in MODHYDROLOG.

Acknowledgements

The optimization of model parameters for the 28 unregulated catchments is part of a project on the estimation of the potential regional impacts of climate change on hydrology and water resources funded by the National Greenhouse Advisory Committee through the Australian Greenhouse Research Grants Scheme. The climate data are provided by the National Climate Centre of the Australian Bureau of Meteorology and the streamflow data are obtained from the respective Australian State and Territory water agencies.

References

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.

Brown, J.A.H., 1987. Estimating streamflows for water development projects in tropical regions. In: Proc. Engineering Conf., Darwin, May 1987, Inst. Eng. Aust., Canberra, Nat. Conf. Publ. 87/1, pp. 343–349.

Chiew, F.H.S., 1990. Estimating groundwater recharge using a surface and groundwater model. Ph.D. Thesis, Department of Civil and Agricultural Engineering, University of Melbourne, Victoria, 357 pp.

Chiew, F.H.S. and McMahon, T.A., 1990. Estimating groundwater recharge using a surface watershed model: sensitivity analyses. J. Hydrol., 114: 305–325.

Chiew, F.H.S. and McMahon, T.A., 1991. Improved modelling of the groundwater processes in MODHYDROLOG. In: Proc. Int. Hydrology and Water Resources Symp., Perth, Western Australia, October 1991, Inst. Eng. Aust., NOAA, Silverspring, MD, Nat. Conf. Publ. 91/22(2), pp. 492–497.

Chiew, F.H.S. and McMahon, T.A., 1993a. Australian data for rainfall–runoff modelling and the calibration of models against streamflow data recorded overdifferent time periods. Civ. Eng. Trans., Inst. Eng. Aust., CE35(3), in press.

Chiew, F.H.S. and McMahon, T.A., 1993b. Assessing the quality of catchment streamflow yield estimates. Aust. J. Soil Res., in press.

Chiew, F.H.S., Stewardson, M.J. and McMahon, T.A., 1993a. Comparison of six rainfall–runoff modelling approaches. J. Hydrol., 147: 1–36.

Chiew, F.H.S., Whetton, P.J., McMahon, T.A. and Pittock, A.B., 1993. Simulation of the impacts of climatic change on runoff and soil moisture in Australian catchments, in preparation.

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

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

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

Monro, J.C., 1971. Direct search optimisation in mathematical modelling and a watershed model application. Tech. Mem. NWS HYDRO-12, National Oceanic Atmospheric Administration, National Weather Service, US Department of Commerce, NOAA, Silverspring, MD, 52 pp.

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

Nandakumar, N., 1989. A methodology to evaluate the effect of climate change on catchment hydrology. M.Eng.Sc. Thesis, Department of Civil and Agricultural Engineering, University of Melbourne, Victoria, 230 pp.

Nash, J.E. and Sutcliffe, J.V., 1970. River forecasting through conceptual models, 1. a discussion of principles. J. Hydrol., 10: 282–290.

Nathan, R.J. and McMahon, T.A., 1988. Application of a rainfall–runoff model using synthetic rainfall data. In: Proc. Conf. on Agricultural Engineering, Hawkesbury, N.S.W., September 1988, Inst. Eng. Aust., NOAA, Silverspring, MD, Nat. Conf. Publ. 88/12, pp. 302–306.

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettanay, E., 1975. A Description of Australian Soils. CSIRO, Wilke and Co. Ltd, Melbourne, 170 pp.

Porter, J.W., 1972. The synthesis of continuous streamflow. Ph.D. Thesis, Department of Civil Engineering, Monash University, Victoria, 222 pp.

Porter, J.W., 1988. Flood simulation model applied to reconstructed reservoir inflows. In: Proc. Hydrology and Water Resources Symp., Canberra., February 1988, Inst. Eng. Aust., NOAA, Silverspring, MD, Nat. Conf. Publ. 88/1, pp. 152–156.

Porter, J.W. and McMahon, T.A., 1975. Application of a catchment model in south eastern Australia. J. Hydrol., 24: 121–134.

Porter, J.W. and McMahon, T.A., 1976. The Monash model: user manual for daily program

HYDROLOG. Res. Rep. 2/76, Department of Civil Engineering, Monash University, Victoria, 41 pp.
Sargent, D.M., 1986. Rainfall–runoff model versus regression in extending monthly streamflows. In: Proc. Hydrology and Water Resources Symp., Brisbane, November 1986, Inst. Eng. Aust., NOAA, Silverspring, MD, Nat. Conf. Publ. 86/13, pp. 74–78.
Weeks, W.D. and Hebbert, R.H.B., 1980. A comparison of rainfall–runoff models. Nord. Hydrol., 11: 7–24.
Wong, T.H.F. and Mustinov, M., 1987. Parameter optimization of the Monash Model in an arid catchment. Civ. Eng. Trans., Inst. Eng. Aust., CE29(4): 205–210.

Appendix

The daily rainfall–runoff model, MODHYDROLOG, has 19 parameters. However, the optimization of much fewer parameters is sufficient to provide adequate estimates of streamflow for most applications. The number of parameters that should be optimized will depend on the catchment to which the model is applied and on the quality of flow estimates required. The relative importance of the 19 parameters is described in this Appendix to guide model users in the selection of the parameters that they should optimize.

The relationships between parameter values and catchment characteristics (see Table 2 for classifications used to describe the predominant catchment soil type and catchment cover), based on the application of MODHYDROLOG to the 28 catchments covering a wide range of physical and climatic conditions, are also given where possible. It must be stressed that the correlations are generally poor and are not statistically significant (at the 5% level). Nevertheless, the use of these recommended values as initial parameter values should assist model calibration, particularly when a manual optimization procedure is adopted. Lower and upper limits to the parameter values are also given to ensure that the processes are simulated realistically. All parameter values assume the use of SI units, where daily rainfall and potential evapotranspiration input data have units of millimetres.

INSC (interception store capacity) (0.5–6.0)

INSC is a fairly important parameter. It can be set to 0.5 for catchments where the runoff coefficient is greater than 0.3. It should, however, be optimized for other catchments. There is a fair correlation between INSC and catchment cover (the values in brackets should be used for arid and semiarid catchments where annual rainfall is less than 500 mm): grass, 1.5 (3.0); mixture, 2.0 (4.0); forest, 2.5 (5.0).

COEFF (maximum infiltration loss parameter) (20–400)

COEFF is a fairly important parameter. It should be optimized if good streamflow estimates are required. However, COEFF is highly correlated to *SQ*, and COEFF can be set to the recommended value if only approximate estimates of runoff are required. There is only a weak correlation between COEFF and the predominant catchment soil type: clay, 120; loam, 130; duplex, 140; sand, 150.

SQ *(exponent in infiltration capacity equation) (0–10)*

SQ is an extremely important parameter and it is difficult to relate it to any catchment characteristic. A value of 3 may be used as an initial estimate, but *SQ* should be optimized in all modelling applications.

ADS (fraction of total area which is depressional) (0–1); DSC (depression store capacity) (0–50); MD *(exponent in depression flow equation) (set to 1.0)*

Simulation of depression flow is not essential and ADS and DSC can be set to zero for all applications. The optimization of these parameters may provide small improvements to runoff estimates for shorter time periods (for example, 1 day). However, the effort required to optimize these additional two parameters is seldom worthwhile.

SUB (constant of proportionality in interflow equation) (0–1)

The simulation of interflow may improve the overall simulation of runoff in certain catchments. However, setting SUB to zero will still provide practically similar estimates of runoff compared with when SUB is optimized, because larger estimates of runoff can usually be simulated by other runoff components. There is only a poor correlation between SUB and catchment soil type: sand, 0.05; loam, 0.15; duplex, 0.2; clay, 0.4.

CRAK (constant of proportionality in groundwater recharge equation) (0–2)

CRAK is an extremely important parameter and should be optimized in all modelling applications. However, the simulation of recharge is not required in arid catchments (CRAK can be set to zero when the annual rainfall is less than 300 mm). There is a weak correlation between CRAK and catchment soil type, and the relationship below can be used to select an appropriate initial value for CRAK (the values in brackets should be used if the annual rainfall exceeds 1500 mm): sand, 0.7 (1.4); loam, 0.5 (1.0); clay/duplex, 0.2 (0.4).

SMSC (soil moisture store capacity) (20–400)

SMSC is an extremely important parameter and should be optimized in all modelling applications. There is a weak correlation between SMSC and the predominant catchment soil type (the values in brackets should be used if the catchment cover is classified as 'forest'): sand, 165 (210); duplex/loam, 180 (230); clay, 210 (270).

EM *(maximum plant-controlled rate of transpiration) (5–20)*

There is a reasonable correlation between *EM* and the catchment cover. The parameter is not particularly important and can be set to the recommended value: grass, 10; mixture, 8.5; forest, 7.

LOCATE (set to 1 for Southern Hemisphere, and 7 for Northern Hemisphere); SEAS (parameter for seasonal fluctuation) (0–1)

SEAS may improve the estimates of runoff for arid catchments and the user may wish to optimize it for applications in catchments where the annual rainfall is less than 500 mm. However, setting SEAS to zero should be sufficient for almost all applications.

CO *(routing coefficient) (1–50)*

There is a reasonable correlation between *CO* and the catchment stream length and slope. The parameter is not important in the estimation of runoff volumes over long time periods (more than 1 week) and can be set to the recommended value. However, the optimization of *CO* may be essential for the satisfactory estimation of flow volumes over shorter time periods (for example, daily).

$\frac{(\text{stream length})^{3/2}}{\sqrt{\text{catchment slope}}}$	*CO*
> 150 000	20
100 000–150 000	15
50 000–100 000	10
< 50 000	5

POWER (routing exponent) (0–1)

POWER is not an important parameter and can be set to zero to allow a linear storage effect in the routing of runoff to the catchment outlet.

K*1 (parameter in linear part of the stream–aquifer interaction equation) (0–1)*

$K1$ is an important parameter and it is difficult to relate it to any catchment characteristic. A value of 0.04 may be used as an initial estimate, but $K1$ should be optimized in all modelling applications. Baseflow contributions are small in arid catchments with ephemeral streams, and the user can set $K1$ to zero in such catchments (where annual rainfall is less than 300 mm).

K*2 (parameter in exponential part of the stream–aquifer interaction equation) (0–1);* K*3 (exponent in exponential part of the stream–aquifer interaction equation) (0–100)*

A linear equation (with $K1$ optimized) is sufficient to simulate baseflow adequately in most catchments, and $K2$ and $K3$ can be set to zero. The user should only optimize $K2$ and $K3$ in catchments where the water from the stream may be recharging an aquifer.

VCOND (constant of proportionality in the deep seepage equation) (0–0.5)

The simulation of deep seepage is not important in temperate catchments with high runoff coefficients (> 0.3) and VCOND can be set to zero in these catchments. The optimization of VCOND is, however, very important in catchments with small runoff coefficients (< 0.1) where deep seepage may represent a significant portion of rainfall water that is lost to the catchment. It is difficult to relate VCOND to surface characteristics of the catchment, and a value of zero may be used as an initial estimate.

DLEV (parameter in deep seepage equation) (−10 to 10)

DLEV has a very little effect on the simulation of runoff unless the catchment receives a large amount of water from areas outside the catchment surface boundary (for example, upwards movement of water from a deep aquifer). It can be set to −0.1 for almost all applications.