The SFB Model Part I — Validation of Fixed Model Parameters

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SUMMARY An investigation into the validity of the two most important fixed parameters of the SFB model is described. The original SFB model and two modified versions of it were applied to 33 catchments encompassing a range of climatic and geomorphological characteristics. It is concluded that the original values of the two fixed parameters investigated could not be improved upon.

1. INTRODUCTION

The civil or agricultural engineer often needs to estimate catchment yield using rainfall data. Methods for solving this problem range from the simple application of an overall runoff coefficient, to the sophisticated use of computers to simulate the rainfall-runoff process. A decision needs to be made early in the design process on how best to match the complexity of the solution to the scale and objectives of the problem at hand. For many problems, one major factor that often influences this decision is that streamflow records are seldom available for small rural catchments.

In the design of small dams, for example, the runoff from the catchment is often estimated as a percentage of annual rainfall (e.g. Nelson (1)). While this approach has the merits of simplicity and readily available data , it cannot be regarded as reliable. It is thus reasonable to suggest that considerable savings in construction cost could be achieved if a more rational design method could be used.

One design tool receiving increasing attention is the SFB rainfall-runoff model developed by Boughton (2). This model may be used to estimate monthly streamflow using historical daily records of concurrent rainfall and evapotranspiration data. In developing the model, Boughton intended for it to be used to estimate yield in ungauged catchments.

The SFB model retains much of the structure of the original Boughton (3) model, though it only requires three parameters to be specified by the user; the deceptive simplicity of the model is in part achieved by fixing a number of parameters that govern its structure. This paper describes an investigation into whether or not the values of these fixed parameters could be improved upon.

2. DESCRIPTION OF CATCHMENTS

A total of 33 catchments were selected for the study. The list of catchments selected and the length of the available record for calibration are listed in Table 1. The catchment areas and the fraction of catchment covered by dense and medium forest are also shown in Table I. From this information it may be seen that the catchments selected range in size from 2 to 251 km^2, and in forest cover from 0% to 100%.

The catchments were also selected to encompass a range of climatic and geomorphological characteristics. The catchments range from a summer-dominant regime in the Hunter and Macleay basins in mid to northern New South Wales, down to the winter-dominant regime of the Latrobe basin in south-eastern Victoria. The majority of the remaining catchments are located in the Ovens and Upper Murrumbidgee river basins.

TABLE I
CHARACTERISTICS OF STUDY CATCHMENTS

Station Number	Stream Name	Calibration Period (month)	Area (km^2)	Fraction Forested (%)
206009	Tia R	254	251	0.68
206010	Yarrowitch R	245	70	0.74
206020	Styx R	238	78	0.49
210011	Williams R	192	196	0.59
210022	Allyn R	192	205	0.97
210042	Foy Bk	209	182	0.91
210049	York Ck	48	11	0.18
210069	Muggyrang Ck	161	5	0.64
210076	Antiene Ck	166	13	0.40
210084	Glennies Ck	196	222	0.45
210095	Bucks Ck	45	2	1.00
210104	Williams R	102	42	0.96
215004	Corang R	87	166	0.84
226017	Jacob's Ck	228	36	0.74
226209	Moe R	311	225	0.03
226213	Morwell R W. Br.	92	12	1.00
226406	Little Morwell R	245	54	0.56
226410	Traralgon Ck	301	86	0.85
226411	Flynns Ck	91	98	0.53
226415	Traralgon Ck	90	141	0.76
229210	Crystal Ck	60	10	0.95
403217	Rose R	144	176	1.00
403224	Hurdle Ck	144	155	0.64
403226	Boggy Ck	120	111	0.60
403232	Morses Ck	144	128	0.94
405256	Corduroy Ck	116	40	1.00
405279	Wappentake Ck	61	89	0.48
410067	Big Badja R	100	220	0.71
410075	Kybeyan R	168	69	0.60
410114	Killimcat R	98	23	0.00
410713	Paddy's R	96	228	0.51
410739	Tidbinbilla Ck	174	25	0.94
410743	Jerrabomberra R	100	54	0.63

3. DESCRIPTION OF CLIMATE DATA

The following two sections briefly outline the approach taken in deriving catchment rainfall and evaporation data suitable for input to the SFB rainfall-runoff model.

3.1 Rainfall Data

Rainfall stations were simply selected on the basis of their temporal and spatial relevance to the study catchments. Daily values of lumped catchment rainfalls were derived using the objective method of Thiessen (4) weighting, and no attempt was made to apply areal reduction factors.

The spatial and temporal distribution of rainfall as well as its quantity is highly variable, and consequently rainfall input errors are a significant source of modelling uncertainty, especially in the upland areas typical of many of the study catchments (5,6,7). Considering the likely shortcomings in the rainfall data, it was decided to incorporate an input data scaling parameter in the rainfall-runoff model. Inclusion of such a parameter would allow the factoring of the rainfall input to account for deficiencies caused by topographical influences, ambient wind conditions, and differences in elevation. This approach has been taken with other models, for example the National Weather River Forecast System (5). The scaling parameter should not be viewed merely as a 'fudge factor' as its magnitude is governed by taking account of the water balance of the catchment. A discussion on the selection of this parameter is included in Section 5.2.

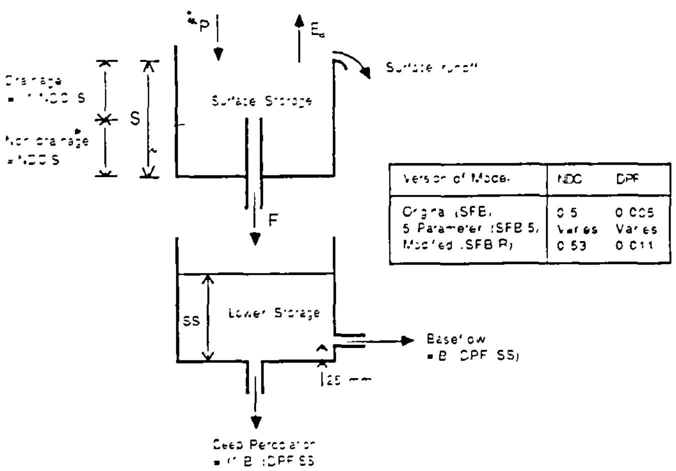
3.2 POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration data was obtained using the wet environmental estimates of Morton (8). Discussion on the use of Morton's procedure to derive potential estimates of evapotranspiration is included in the second accompanying paper (9). It is worth commenting, however, that the estimation of Morton's wet environmental evaporation does not make use of the complementary relationship of Bouchet (10), and as such the assumptions underlying its use on a daily basis are the same as those for the Penman (11) equation.

It was also decided to incorporate a factor in the rainfall-runoff model for scaling the evapotranspiration data input. The reasons for this are as discussed above for the factoring of rainfall input data, and arise from the need to account for the spatial variability of evapotranspiration.

4. DESCRIPTION OF THE MODELS USED

The SFB model and two modified versions of it were applied to the study catchments. The forms of the models used are described in the following three sections. A schematic diagram of the three models is shown in Figure 1.



Version of Model	NDC	DPF
Original (SFB)	0.5	0.005
5 Parameter (SFB-5)	Varies	Varies
Modified (SFB-R)	0.53	0.011

Figure 1. Schematic diagram of models used in the study.

4.1 Original Three Parameter Version (SFB)

The simple structure and small number of parameters of the SFB model does not readily reflect the degree of research and experience that has gone into its development. The model retains the conceptual basis of the original Boughton model (3), an 8 parameter physically-based model that has been widely used in Australia. An important difference exists in that, in line with the modifications developed by McMahon and Mein (12), the SFB model simulates baseflow. Extensive experience in use of the original 1966 version enabled Boughton to fix the value of some of the model parameters so that only 3 require calibration. A brief discussion of the SFB model follows, in which attention is drawn to the fixed nature of some of the operational aspects of the model.

The three parameters that require calibration are: S, the surface storage capacity of the catchment; F, the daily infiltration capacity controlling percolation from the surface store to the groundwater store; and B, a baseflow factor that determines the portion of the daily depletion of groundwater that appears as baseflow runoff. The drainage component of the surface storage capacity is fixed at one half of the surface storage capacity; drainage from this store will occur at the rate of F mm/day until the drainage component of the store empties.

The lower store is depleted each day by the fixed fraction of 0.005 of water remaining in the store. The baseflow parameter B determines how much of this water appears as baseflow in runoff and how much is lost in deep percolation. If B = 1.0, then all of the water depleted from the lower store becomes baseflow, and if B = 0.0 then baseflow is zero. There has to be at least 25 mm of water in the lower store before any baseflow occurs.

The non-drainage component of the surface store is depleted each day by evapotranspiration. When this component is full, then evapotranspiration occurs at the potential rate (E_{pot}). When the non-drainage component of the surface store is not full, then an actual rate of evapotranspiration (E_a) is determined by:

$$E_a = \mathrm{Min}\left\{E_{max}\left(\frac{s}{0.5S}\right);\ E_{pot}\right\} \qquad (1)$$

in which 0.5S is equal to the non-drainage capacity of the surface store, s is the water level in the store, and E_{max} is the maximum, limiting rate of evapotranspiration that could occur, which is fixed at 8.9 mm/day. This function is an approximation of the relationship between actual and potential evapotranspiration determined by Denmead and Shaw (13), and is diagrammatically illustrated in Figure 2.

Surface runoff (Q_s) occurs once the surface store is full. The form of the surface runoff relation forms the basis of the effective precipitation model described above, and may be written:

$$Q_s = P - F\tanh\left(\frac{P}{F}\right) \qquad (2)$$

in which P is the amount of rain remaining after filling the surface store, and F is the infiltration parameter.

4.2 Five Parameter Modified Version (SFB-5)

The two most important fixed parameters governing the structure of the SFB model are (i) the fixed equal division between the drainage and non-drainage components of the surface store, and (ii) the 0.005 fraction of lower storage depletion rate.

To test the suitability of these values, the model was modified to allow these parameters to vary, thus resulting in a model that requires 5 parameters to be fitted by calibration.

The parameter governing the rate of lower storage depletion rate is referred to as DPF, and the parameter governing the division of

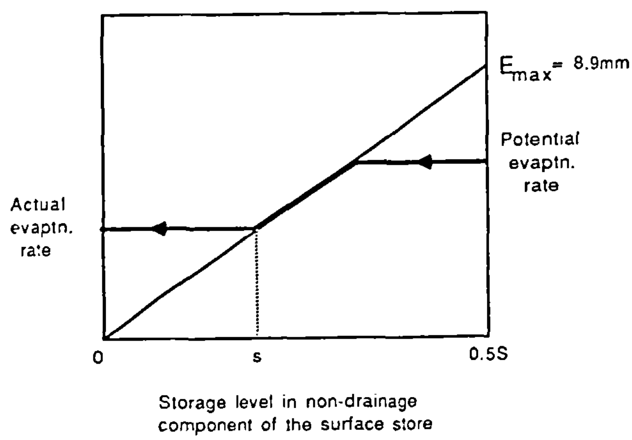


Figure 2. Illustration of method used to determine actual evapotranspiration.

the surface storage between the drainage and non-drainage components is NDC. The parameter NDC is defined as the fraction of the upper storage that is non-draining, and thus the drainage component is defined as (1.0-NDC)S.

4.3 Modified 3 parameter SFB model (SFB-R)

The third model used is the same as the original SFB model, except that the values of the fixed DPF and NDC parameters were replaced by the optimum values as determined by calibration of the SFB-5 model to all the study catchments.

5. DESCRIPTION OF COMPARATIVE ANALYSIS

5.1 Overview

The comparative analysis undertaken may be summarised by the following 3 steps:

1. The 3 parameter SFB model was applied to all study catchments, and a number of performance characteristics were calculated and recorded.

2. The 5 parameter version of the SFB model (SFB-5) was then applied to all catchments, and the same performance characteristics as measured in step 1 were evaluated.

3. The average values of the two floating parameters (NDC and DPF) were calculated, and were then input as fixed values into a three parameter version of the SFB model (SFB-R); all relevant performance characteristics were obtained.

This approach thus make it possible to determine whether or not the two fixed parameters (NDC and DPF) constrain model performance, and whether or not the value of the fixed parameters are suited to the wide range of catchment conditions considered.

5.2 Calibration Approach

In order to calibrate the model, a set of initial parameter values was selected using recommendations contained in Boughton (2). The model was then optimised using the Simplex algorithm developed by Nelder and Mead (14) using an objective function based on the square of the differences between the square root of the observed and simulated monthly flows. The square root of the monthly flows was used so that the model fit at high flows did not dominate the calibration, emphasis thus being given to the estimation of yield rather than flood events.

Once the approximate value of the parameters was determined, the initial values of the upper and lower stores were chosen by trial and error such that the difference between the observed and simulated monthly flows for the initial period was minimised; although the first 12 months of the record was used for this trial and error process, it was generally found that the effect of the initial storage levels did not extend past the first 3 to 4 months.

Data input factors were determined by observing any consistent discrepancies between the volumes of simulated and observed streamflow. If, regardless of the initial parameter values selected, the model converged to an optimum that indicated a consistant bias of greater than 10% in the difference between simulated and observed streamflow volumes, then either the rainfall and/or evaporation data were factored to correct the bias. The data input factors were chosen to lie within between 0.7 to 1.3, as it is considered that any variation outside this range is not realistic.

At least three different sets of initial values of the model parameters were used to initialise the Simplex optimisation procedure. Where different sets of optimised parameters were found, a number of different performance criteria were inspected in order to adopt the best set of parameters. The performance criteria used, in decreasing order of importance, were: the comparison between the means and standard deviations of observed and simulated flows, the coefficient of determination, the standard error of predicted values, the coefficient of efficiency, and the residual mass curve between observed and simulated monthly flows (15).

The models were calibrated using all available record. A split sample test (16), or the more stringent procedures outlined by Klemes (17), were not undertaken. While such procedures normally constitute an important step in the calibration process, they were not used in this study largely because of time constraints; use of a split sample data sample would require 2 to 3 times more effort than that used in the adopted approach. Also, the emphasis of this study is on the comparison of model performance, where it was considered more important to consider a range of catchment conditions rather than the validity of the derived calibration.

5.3 Summary of Results

The calibration results of the three models are summarised in Table II. The two goodness-of-fit criteria reported are the coefficient of determination between observed and simulated monthly flow volumes (R^2), and the difference between the total observed and simulated flow volumes (ΔV).

Non-uniqueness of finding an optimal solution is particularly important when attempting to relate the values of the parameters to physical catchment characteristics. The practical difficulties of determining a unique set of optimum parameters has been clearly illustrated by Johnston and Pilgrim (18), where a true set of optimum parameters could not be found in over two years of full-time work concentrated on a single catchment. If the true value of a parameter cannot be found, then there is little point in undertaking regression analysis as parameter uncertainty will confound any attempt to obtain correlations of physical significance. Table II thus also indicates whether or not the model converged to a global optimum; in this context, a global optimum is deemed to exist if the model converges to roughly the same set of parameter values for all three different sets of initial starting conditions.

6. DISCUSSION OF RESULTS

The results summarised in Table II indicate that the original SFB model has variable success in simulating the rainfall-runoff process. The best set of calibration results were obtained for station number 210011, where an R^2 of 0.91 and a ΔV of 0% was obtained; Figure 3(a) shows a sample comparison between the observed and simulated hydrographs. One of the worst set of results was obtained for station number 229210, where an R^2 of 0.34 was achieved, and the associated model fit is illustrated in Figure 3(b). The largest difference between simulated and observed streamflow volumes was -28%, which was obtained for station number 405256. The ΔV criterion could have been improved by applying data input factors outside the range of 0.7 to 1.3, but it was considered that adoption of more extreme factors would merely reduce the magnitude of ΔV without improving the form of the fit (as reflected in the magnitude of the square of the differences between the square root of the observed and simulated monthly flows). The results also suggest that a global optimum is always achieved with the SFB model - this is in fact not the case, for, although not reported here, the SFB model was applied to a further 135 catchments where it was found that a global optimum was clearly evident in around 60% of cases (9).

The results for the 5 parameter version of the model are somewhat surprising. It would be expected that a better fit could be achieved using a 5 rather than a 3 parameter model, as an increase in the number of parameters allows a greater degree of freedom with which to minimise the objective function. However, the improvement in model results does not reflect the notional two-thirds increase in model flexibility. A higher R^2 was achieved in a majority of cases, though the magnitude of the overall mean improvement was only 0.05; with reference to the higher standard deviation obtained, it can be seen that calibrating five parameters resulted in a slightly more variable set of results (0.25 compared to 0.15). A reduction in ΔV was achieved in around half the cases, resulting in an overall mean improvement of only 1%, though the variability of the results with respect to this crtiterion is around the same as that for the original model. It is also worth

TABLE II

CALIBRATION RESULTS FOR THE SFB, SFB-5 AND SFB-R MODELS.

Station	Original SFB model Results (DPF=0.005 and NDC = 0.50)						SFB-5 Results (DPF and NDC varying)					SFB-R Results (DPF=0.011, NDC = 0.53)		
Number	S (mm)	F (mm/day)	B	R^2 [1]	ΔV (%) [2]	Global [3]	DPF	NDC	R^2 [1]	ΔV(%) [2]	Global [3]	R^2 [1]	ΔV(%) (2)	Global [3]
206009	101	3.1	0.87	0.55	-6	Y	0.009	0.46	0.59	0	Y	0.59	-1	
206010	177	2.0	0.80	0.54	-5	Y	0.010	0.62	0.59	3	Y	0.56	0	Y
206020	37	10.3	1.00	0.65	-14	Y	0.023	0.26	0.72	-10		0.69	13	Y
210011	76	2.5	0.73	0.91	0	Y	0.015	0.74	0.92	-2	Y	0.91	1	
210022	73	3.2	0.89	0.89	0	Y	0.018	0.15	0.90	1		0.90	-1	
210042	70	1.9	0.42	0.67	7	Y	0.006	0.58	0.67	-3	Y	0.66	3	
210049	117	0.9	0.18	0.92	-8	Y	0.007	0.60	0.92	-11		0.91	11	
210069	134	1.1	0.42	0.84	4	Y	0.002	0.77	0.86	4		0.85	-7	
210076	65	0.6	0.67	0.75	3	Y	0.003	0.76	0.76	4		0.74	-5	
210084	205	2.0	0.40	0.80	-9	Y	0.003	0.50	0.80	-11	Y	0.79	6	
210095	125	0.1	0.98	0.87	0	Y	0.009	0.61	0.87	0		0.87	-1	
210104	42	4.0	0.99	0.50	-22	Y	0.017	0.51	0.51	-20		0.50	20	Y
215004	45	0.8	0.96	0.73	-12	Y	0.007	0.76	0.73	-13		0.73	9	Y
226017	89	1.6	0.63	0.85	-1	Y	0.010	0.48	0.87	-1	Y	0.87	1	Y
226209	149	0.7	1.00	0.72	-2	Y	0.012	0.63	0.76	4	Y	0.71	0	
226213	127	4.0	0.66	0.56	-3	Y	0.007	0.90	0.75	0	Y	0.66	1	Y
226406	96	3.9	0.75	0.41	-3	Y	0.012	0.17	0.58	-1		0.53	2	Y
226410	130	0.9	0.78	0.80	2	Y	0.010	0.90	0.86	1	Y	0.82	-4	Y
226411	412	1.3	0.39	0.72	1	Y	0.021	0.16	0.79	1	Y	0.78	2	Y
226415	132	0.8	0.72	0.88	8	Y	0.006	0.83	0.88	6	Y	0.88	-6	Y
229210	87	4.0	0.71	0.34	-6	Y	0.008	0.30	0.40	-5		0.34	0	
403217	179	0.5	0.99	0.77	-6	Y	0.026	0.61	0.86	0		0.78	3	Y
403224	137	1.2	0.61	0.67	-2	Y	0.015	0.11	0.69	2		0.68	0	Y
403226	171	1.3	0.86	0.77	-4	Y	0.013	0.43	0.85	1	Y	0.81	4	Y
403232	161	2.0	0.66	0.66	-4	Y	0.016	0.42	0.80	0	Y	0.75	6	Y
405256	156	0.9	1.00	0.79	-28	Y	0.014	0.53	0.80	-22		0.81	27	
405279	63	0.6	0.31	0.83	-1	Y	0.008	0.59	0.87	-1	Y	0.85	-5	Y
410067	168	2.0	0.61	0.63	3	Y	0.005	0.52	0.63	3	Y	0.57	-5	
410075	108	1.4	0.65	0.87	-3	Y	0.011	0.34	0.87	-3	Y	0.86	1	
410114	132	1.1	0.31	0.84	4	Y	0.004	0.56	0.83	1	Y	0.84	-5	Y
410713	118	0.8	0.92	0.58	-5	Y	0.007	0.58	0.71	0		0.61	-6	
410739	85	1.9	0.99	0.70	-5	Y	0.007	0.47	0.73	-2	Y	0.72	1	
410743	152	0.6	0.31	0.53	-5	Y	0.013	0.78	0.66	-9	Y	0.58	1	
			Mean:	0.71	-4		0.011	0.53	0.76	-3		0.73	2	
			Std. Dev.:	0.15	7		0.006	0.21	0.25	7		0.14	7	

Notes:
[1] Coefficient of determination between monthly observed and simulated streamflow volumes
[2] Difference between total volume of observed and simulated streamflow volumes.
[3] The symbol "Y" signifies that a global optimum was achieved.

noting that the number of cases in which a global optimum was achieved fell to around 60%.

Allowing the values of NDC and DPF to vary resulted in a mean calibrated value of 0.53 for NDC, and 0.011 for DPF. In the original SFB model, these parameters are fixed at 0.5 and 0.005, respectively. It is thus seen that the values of the fixed parameters are not too dissimilar to the mean values obtained by calibration.

Replacing the original fixed values of NDC and DPF by the mean values obtained by calibration does not significantly improve model performance. The results listed in Table II indicate that for the majority of catchments there is little change in R^2; again, a reduction in ΔV was achieved in only around half the cases, resulting in an overall mean improvement of about 2%. Also, the new values of NDC and DPF resulted in an global optimum not being identified in approximately half the catchments considered. It is also interesting to note the reversal in sign of many ΔV values between the SFB-5 and SFB-R results; this can perhaps be partly explained by the combined effect on streamflow volume of the different values of the DPF and NDC parameters, where, particularly in the case of NDC, adoption of a higher (or lower) value than that obtained by calibration would result in a higher (or lower) fraction of the lower store appearing as baseflow.

While it is seen that there is a slight increase in model performance with the revised values of DPF and NDC, it is felt that the increase is too slight to offset the disadvantages associated with a decrease in the ability of the model to converge to a global optimum.

7. SUMMARY AND CONCLUSIONS

The two most important fixed parameters governing the structure of the SFB model are (i) the fixed equal division between the drainage and non-drainage components of the surface store, and (ii) the 0.005 fraction of lower storage depletion rate. The model was modified to allow these two parameters to vary, and was then applied to 33 catchments of varying climatic and geomorphological characteristics. The mean values of these two parameters as determined by calibration were then used in place of the original values fixed in the model, and the modified model was then applied to the 33 catchments.

It was found that the values of the fixed parameters in the SFB model could not be improved upon; while a slight overall increase was observed in the coefficient of determination between simulated and observed monthly flows and the difference between observed and simulated streamflow volumes was slightly improved, there was a decrease in the ability of the model to converge to a global optimum. A decrease in the ability of the model to converge to a global optimum is considered a disadvantage if it is desired to regionalise model parameters.

It is therefore concluded that the SFB model should be used as originally proposed by Boughton (2).

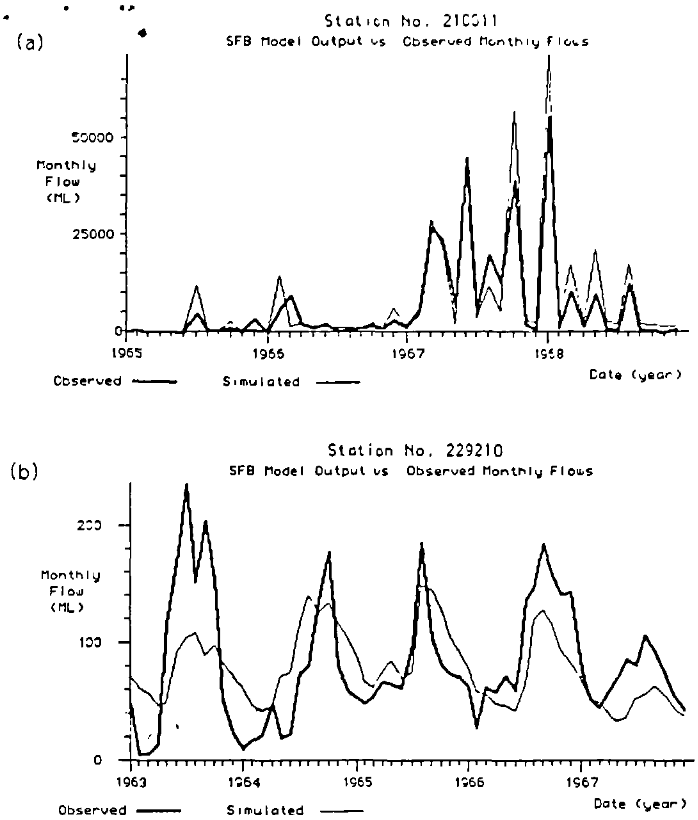


Figure 3. Example of observed and simulated hydrographs for the (a) best and (b) worst set of results.

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