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POTENTIAL AND LIMITATIONS OF RAINFALL–RUNOFF MODELS FOR PREDICTION ON UNGAUGED CATCHMENTS: A CASE STUDY FROM THE PAPUA NEW GUINEA HIGHLANDS

G. Pickup*

ABSTRACT

A modified version of the Boughton model was calibrated for the Tua River Basin in the Papua New Guinea Highlands. The same model parameters were then used to calculate runoff from rainfall for seven other basins to see whether it is possible to transfer model parameters between similar basins. Model parameters could be successfully transferred between similar basins where low flows are concerned, but higher flows were not always successfully reproduced.

INTRODUCTION

Rainfall–runoff models have proved to be a useful tool in hydrological design and prediction. However, their main limitation is that, to produce reliable results, they must be calibrated, i.e. their parameters must be adjusted so that calculated runoff closely matches the runoff which actually occurred. For calibration, it is necessary to have stream gauging data, so model usage is largely restricted to the extension of runoff records on gauged basins.

In the last few years, a number of attempts have been made to extend the area of application of rainfall–runoff models. One example is Australian Water Resources Council Research Project 68/1 which had as one of its aims the derivation of rainfall–runoff model parameters which could be correlated with climate and catchment characteristics (Johnston and Pilgrim, 1973). Other work of this type includes that of James (1970), Ross (1970) and Hendricks and Ligon (1973) with OPSET, a self-calibrating version of the Kentucky version of the Stanford Watershed Model.

In general, attempts to relate model parameters to catchment characteristics have met with failure and have been treated with scepticism (Chapman, 1975; Philip, 1975). It has been increasingly accepted that the automatic calibration techniques used to derive 'optimum' parameter values may in fact yield sub-optimal solutions (Pilgrim, 1975). Furthermore, because of model parameter interdependence, more than one set of parameters may yield equally acceptable results.

Under these circumstances, especially after calibration, model parameters cannot be accepted as having any physical significance, and most rainfall–runoff models are little more than complex multi-path and multi-parameter regression equations (Clarke, 1973). As a result, parameters derived by optimization are similar to the regression coefficients of simpler black-box models.

If rainfall–runoff models are regression equations rather than physically based models, there is no reliable way of estimating their parameter values from the physical characteristics of the system. The only way in which parameter values may be derived is by fitting the model to observed data. Consequently, the only potential for conceptual rainfall–runoff model use on ungauged basins is to calibrate the model on a gauged basin which has been selected as a prototype. The model parameters may then be transferred to ungauged basins with similar characteristics to the prototype in the hope that the rainfall–runoff relationships of the basins are similar.

This paper describes such an approach to runoff estimation for ungauged drainage basins in the Papua New Guinea Highlands using a version of the Boughton (1965) model which has been modified for humid tropical conditions. The model was calibrated on one basin and the model parameters derived were then used to calculate runoff from rainfall on seven other basins. Comparison of calculated runoff with observed runoff on the basins illustrates the extent to which model parameters are transferable and the reliability of runoff estimates for ungauged catchments produced in this way. The paper also demonstrates some of the problems of using this type of approach in areas where data are limited and often of poor quality.

MODEL CHARACTERISTICS

The model used in this study has been described in detail by Pickup (1976), so only a brief description is presented here. It is based on a modified version of the Boughton Model developed by Johnston and Pilgrim (1973). However, a number of changes to model structure and operation were introduced to adapt it to humid tropical basins of up to 3000 km² and to make it easier to calibrate.

The model consists of three storages, three paths by which water may reach the stream channel, and has nine parameters (Fig. 1). The three stores are: the moisture retention store (RET), the drainage store (DS) and the lower soil store (SS). Each store has a finite capacity, these being RETMAX, DSMAX and SSMAX respectively. The moisture retention store represents the ability of the basin to store water, and it can only be emptied by evapotranspiration. It replaces the interception store and the upper soil store in the original Boughton model. The drainage store represents the water held in the topsoil between field capacity and saturation. It operates in the same way as the drainage store in the original Boughton model. The lower soil store represents water held in the subsoil and in shallow aquifers.

The model has a time increment of one day and operates as follows. Rain which falls on the catchment first enters the moisture retention store. If this store is filled, the surplus overflows into the drainage store. Infiltration occurs from the drainage store to the lower soil store according to the relationship used by Johnston and Pilgrim (1973):

$$\mathrm{F} = \mathrm{SSMAX}\,[1 + (1/\mathrm{FK})\,ln\,(1-\mathrm{D} + \mathrm{D.e}^{\mathrm{FK(SS/SSMAX-1)}})]-\mathrm{SS}$$

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* Department of Geography, University of Papua New Guinea.

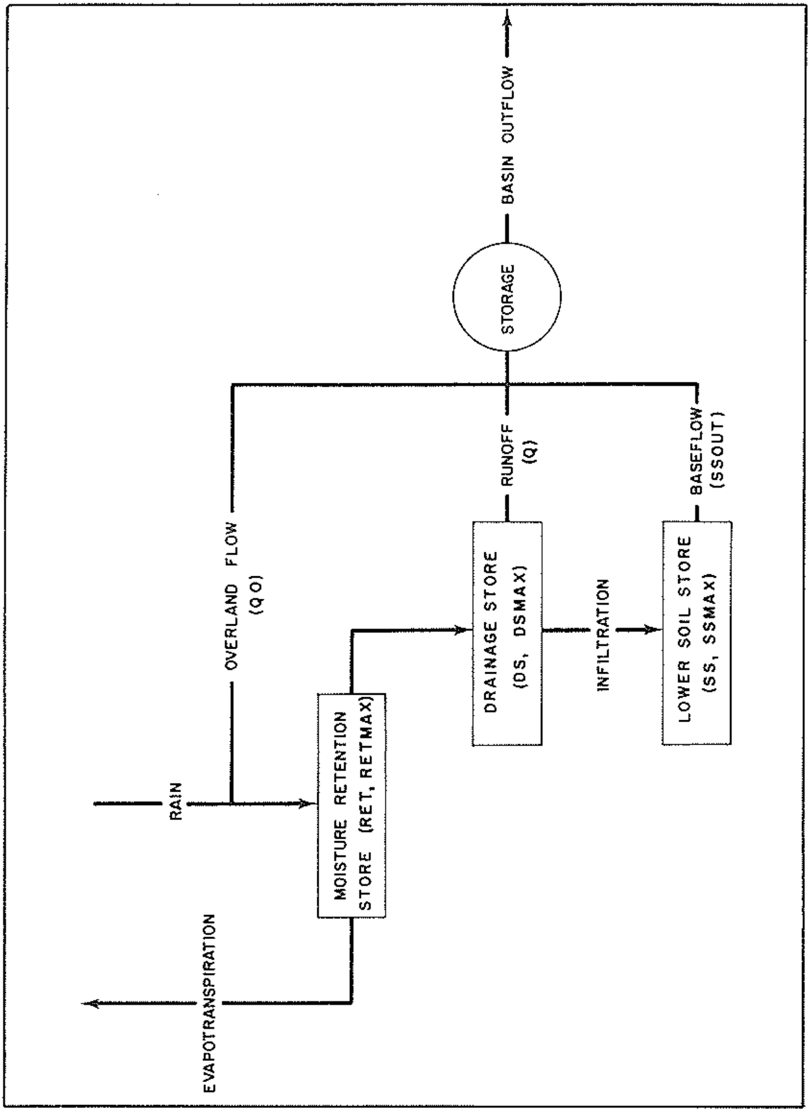

FIG. 1 – Structure of the modified Boughton model.

where $\mathrm{D} = \exp(-\mathrm{FO.FK}.e^{-\mathrm{FK}}/\mathrm{SSMAX})$, F is the daily amount of infiltration, and FO and FK are parameters of the infiltration equation.

Losses from the basin can only occur from the moisture retention store by evapotranspiration. The rate of evapotranspiration depends on the content of the store, and is calculated by a function similar to that used by Johnston and Pilgrim (1973):

$$\text{if } E < (\text{RET.EVPMX})/\text{RETMAX then } \text{RET}_t = \text{RET}_{t-1} - E$$

$$\text{if } E > (\text{RET.EVPMX})/\text{RETMAX then } \text{RET}_t = \text{RET}_{t-1}\, e^{-\text{EVPMX RETMAX}}$$

EVPMX being the limiting rate at which evapotranspiration can occur from the moisture retention store, while E is the potential evapotranspiration.

Water may reach the stream channel by three paths in the model. Firstly, there is the path used in the original version of the Boughton model (Boughton, 1965) in which surplus moisture overflowing the drainage store becomes runoff, the exact amount being calculated from the relationship:

$$Q = P - F.\tanh(P/F)$$

where P is the overflow from the drainage store and F is the daily infiltration. A second path is by seepage from the lower soil store which contributes baseflow. This is calculated from the relationship:

$$\text{SSOUT} = C.\log_{10}\text{SS}$$

where SSOUT is baseflow, C is an empirical coefficient and SS is the current moisture content of the lower soil store. This equation was chosen because it gives a good fit to observed data, rather than for theoretical reasons. The third path by which water may reach the stream channel is by overland flow. Much of Papua New Guinea's rainfall is associated with short-duration, high-intensity thunderstorms, and there is plentiful geomorphic evidence of Horton-type overland flow. This overland flow may reach the stream even when the drainage basin is fairly dry, a situation which could not be handled by the original version of the Boughton model. To allow for overland flow, a relationship analogous to an antecendent-precipitation index was used:

$$\text{QO} = \text{RAIN.CONST.}(\text{DS} + \text{RET})/(\text{DSMAX} + \text{RETMAX})$$

where QO is overland flow, RAIN is daily precipitation, CONST is an empirical coefficient, RET and RETMAX are the current and maximum contents of the moisture retention store, and DS and DSMAX are the current and maximum contents of the drainage store. Thus, a certain proportion of all rainfall becomes overland flow, but the exact proportion decreases as the water held in the moisture retention and drainage stores becomes less, i.e. as the catchment becomes drier.

Once baseflow, overland flow and the overflow from the drainage store reach the stream channel, they are added together and routed through storage. A single linear concentrated storage at the basin outlet is assumed in which storage, S, is directly proportional to the outflow, O:

$$S = KO$$

As Chow (1964, Section 14) has shown, the routing equation for this type of storage reservoir can be expressed using a recession coefficient, thus:

$$O_t = (\text{QO} + Q + \text{SSOUT})(1 - \text{COEFK}) + O_{t-1}.\text{COEFK}$$

where COEFK is the recession coefficient and *t* refers to time.

MODEL APPLICATION

To test the extent to which parameters derived from one drainage basin can be applied to nearby ungauged basins, eight catchments in the Papua New Guinea Highlands with varying characteristics were selected. The location of these basins is shown in Fig. 2, and some of their catchment and climatic characteristics are listed in Tables 1 and 2. The eight catchments cover a wide range of sizes and physical characteristics and were selected to investigate the extent to which a given set of model parameters can be used on basins of similar characteristics, irrespective of size. The information which is available on catchment characteristics is that which might be expected in many operational situations in Papua New Guinea. It consists of maps, aerial photographs and CSIRO Land Research Series Reports.

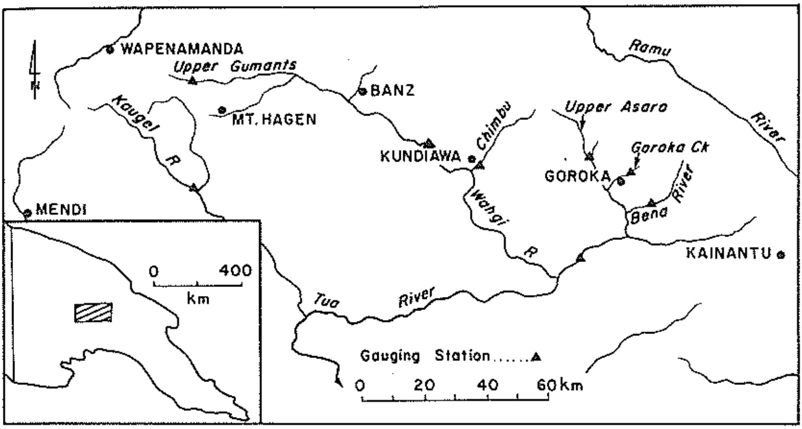

FIG. 2 – Location of drainage basins used in the study.

TABLE 1 – Size and climatic characteristics of drainage basins used in the study. Catchment data from Bureau of Water Resources (1974). Climate data based on McAlpine *et al.* (1975).

Basin	*PNG Station No.*	*Area (km^2)*	*Annual rainfall (mm)*	*Annual pan evaporation* (mm)*
Tua	114	2690	2091	1866
Wahgi	71A	3060	2669	1687
Kaugel	112	580	2811	1300
Upper Gumants	121	36	2778	1568
Bena	57	320	1908	1866
Chimbu	72	600	2090	1886
Goroka Ck.	27A	38	1921	1866
Upper Asaro	35A	240	2980	1866

* Estimated for U.S. Class A Pan.

The model was first calibrated for the Tua River using rainfall and runoff data for 1970 and estimates of evaporation published by McAlpine *et al.* (1975). The first calibration run was made using Rosenbrock's (1960) algorithm, and the objective function F, was calculated as:

$$F = \sum_{i=1}^{n} \left| \mathrm{QOBS}_i - \mathrm{QCALC}_i \right|^2$$

where QOBS is observed daily runoff and QCALC is the computed daily runoff from the model. The calibration run yielded reasonable results, but baseflow was found to decrease too rapidly. The capacity of the lower soil store, SSMAX, was therefore increased and a second calibration run was carried out using the simplex algorithm of Nelder and Mead (1965). A different objective function was used in this run:

$$F = \sum_{i=1}^{n} \left| \mathrm{QOBS}_i - \mathrm{QCALC}_i \right|$$

After the second calibration run the baseflow and flood characteristics of the Tua River were reproduced well, as Fig. 3 shows, and the correlation between observed and modelled daily flows had a value of $r = 0.899$. The final values of the model parameters are listed in Table 3.

After calibration, the model was run for the other seven drainage basins using the parameters derived from the Tua River. Several criteria were used to assess model performance, these being:
(i) the correlation between observed and calculated daily runoff;
(ii) the correlation between observed and calculated monthly runoff;
(iii) the similarity of the observed and calculated flow-duration curves.
The correlation coefficient was used in (i) and (ii) not because it has any special virtues as an index of model performance but because it seems to be the most frequently quoted in the presentation of results (see for instance, Porter and McMahon, 1971, 1975, and Moore and Mein, 1975).

Basin	Main Rock Types	Relief	Soils	Vegetation
Tua	Granodiorite, gabbro, schist, greywacke, shale, lava, volcanic breccia, alluvium and colluvium	Rugged mountains and hill ridges, dissected fan surfaces and slopes, river terraces and floodplains	Peat and humus soils, humic clay soils, colluvial soils, lateritic soils and latosols	Montane and lower montane rain forest, induced grassland, gardens and garden regrowth
Wahgi	Granodiorite, gabbro, schist, greywacke, shale, lava, volcanic ash, mudstone and siltstone; alluvium in valleys	Rugged mountains and hill ridges, fan surfaces (varying dissection), river terraces and floodplains	Peat and humus soils, alluvial and colluvial soils, humic clay soils, lateric soils and latosols, meadow-soils	Montane and lower montane rain forest, induced grassland, gardens and garden regrowth, swamp grassland
Kaugel	Greywacke, tuff, volcanic ash, sedimentary rocks and alluvium	Rugged mountains, hills and hill ridges; volcanic plateaus, plains and slopes; fans and flat valley floors	colluvial and humic brown clay soils	Lower montane rainforest, grassland, sword grass and shrub regrowth
Upper Gumants	Lava, agglomerate, tuff, and volcanic ash	Rugged mountains and hill ridges	Alpine peat and humus soils, humic clay soils	Montane and lower montane rain forest, sword grass and shrub regrowth, induced grassland
Bena	Granodiorite, schist, alluvium and colluvium	Rugged mountains, dissected fan surfaces and floodplains	colluvial and humic clay soils, lateritic and meadow-soils	Lower montane rain forest, induced grassland, gardens and garden regrowth
Chimbu	Granodiorite, schist, siltstone mudstone, conglomerate	Rugged mountains	Alpine peat and humus soils, humic clay soils, latosols	Montane and lower montane rainforest, induced and natural grassland
Goroka Ck.	Granodiorite, schist, alluvium and colluvium	Rugged mountains and hill ridges, dissected fan surfaces	colluvial and humic clay soils	Montane and lower montane rainforest, sword grass, gardens and garden regrowth
Upper Asaro	Granodiorite, schist, alluvium and colluvium	Rugged mountains, dissected fan surfaces, floodplains	Colluvial and humic clay soils, lateritic and alluvial soils	Lower montane rain forest, induced grassland, gardens and garden regrowth, sword grass

TABLE 2 – Geology, relief, soils and vegetation of drainage basins used in the study. Information from Perry *et al.* (1965) and Haantjens *et al.* (1970).

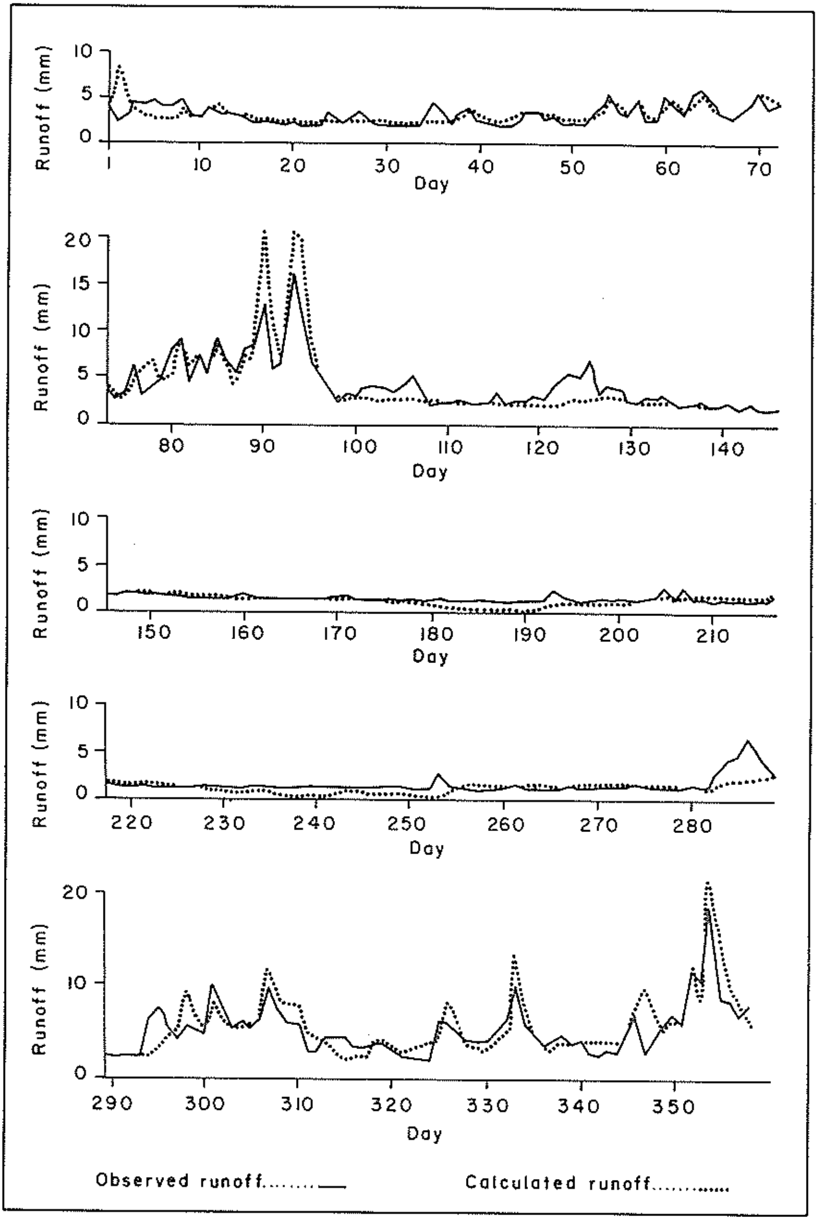

FIG. 3 — Observed and calculated daily runoff for the model calibration period, Tua River, 1970.

Values of the correlation coefficient for observed and calculated daily runoff are presented in Table 4. The correlations are fair except in the case of the Wahgi River, but – predictably – they are not as good as the results produced by calibration. The best result is $r = 0.755$ for the Upper Gumants which is surprising, for as Tables 1 and 2 indicate, this basin is much smaller than the Tua and also has different geological characteristics. Also surprising is the low r value of 0.403 for the Wahgi River. This basin is similar in size to the Tua and has many similar characteristics (Tables 1 and 2).

TABLE 3 – Model parameter values for the Tua River

Parameter	*Definition*	*Value*
SSMAX	Capacity of lower soil store	84.4 mm
RETMAX	Capacity of moisture retention store	4.50 mm
DSMAX	Capacity of drainage store	31.90 mm
COEFK	Routing coefficient	0.442
I O	Parameter of infiltration curve	254
FK	Parameter of infiltration curve	2.68
EVPMX	Maximum evapotranspiration rate which can occur when moisture retention store is full	6.67 mm/day
C	Lower soil store drainage parameter	1.19
CONST	Overland flow parameter	0.358

Anomalies such as these may occur for three reasons. Firstly, some of the observed runoff data may be in error. Secondly, the rainfall input data may contain inaccuracies. Thirdly, the model or the chosen parameter set may be inappropriate for the drainage basin. Each of these reasons will be discussed in turn.

TABLE 4 – Correlations between observed and calculated daily and monthly runoff for seven drainage basins in the Papua New Guinea Highlands using model parameters derived from the Tua River.

Basin	*Year*	*Daily runoff r value*	*Monthly runoff r value*
Wahgi	1970	0.403	0.918
Kaugel	1970	0.631	0.886
Upper Gumants	1969	0.755	0.961
Bena	1970	0.736	0.904
Chimbu	1963	0.675	0.812
Goroka Ck.	1970	0.686	0.871
Upper Asaro	1966	0.702	0.817

Errors in the runoff data certainly do exist. Many of the gauging stations used in this study are inaccessible and therefore visited infrequently. Consequently,

TABLE 5 – Rainfall data availability for drainage basins used in the study.

Basin	*No. of gauges inside basin*	*No. of gauges outside basin*	*Approx. distance to nearest gauge outside basin (km)*
Tua	5	–	–
Wahgi	14	–	–
Kaugel	1	1	8
Upper Gumants	1	–	–
Bena	1	–	
Chimbu	1	1	2
Goroka Ck.	0	1	2
Upper Asaro	0	3	11

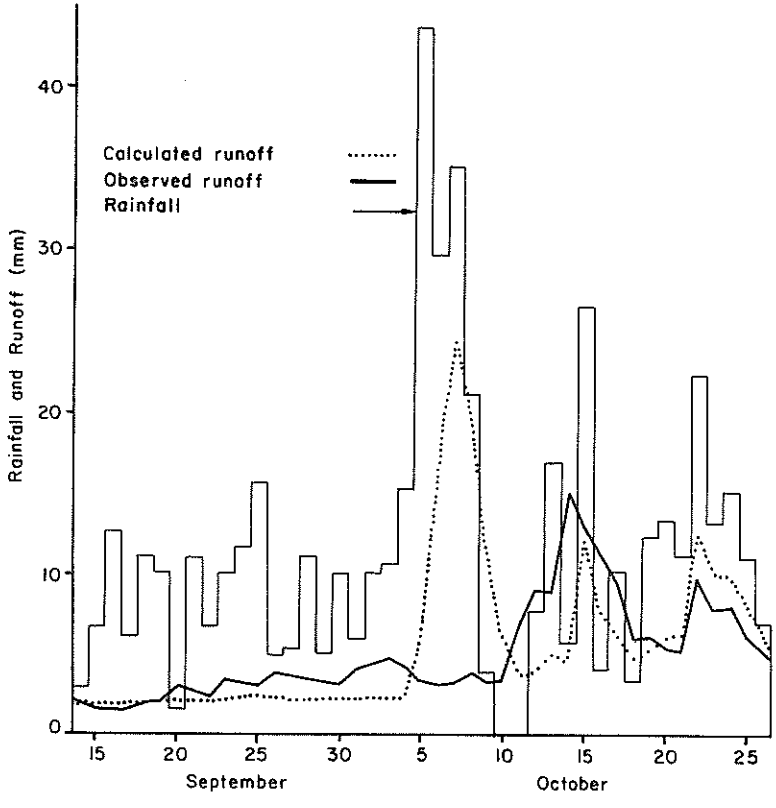

FIG. 4 – Daily rainfall and runoff for the Wahgi River, 14 September to 26 October, 1970. Note the absence of a flood during the storms 5–10 October, although much smaller rainfalls produced floods subsequently.

ratings, especially at high discharges, may be of low quality and runoff records contain errors of ±10 percent (P. Williamson, PNG Bureau of Water Resources, pers. comm.). This problem is likely to be encountered in most model studies of drainage basins in remote areas.

Errors in rainfall input are also likely to exist, particularly where the number of rainfall stations is limited. Dawdy and Bergman (1969), for example, have shown that even with good-quality rainfall data and a small catchment, the use of only one rainfall station restricts the accuracy of flood prediction to no better than 20–25 percent. As Table 5 shows, the rainfall data available for this study were limited. Some basins have only one raingauge within their boundaries while others have none at all.

Most rainfall in the Papua New Guinea Highlands comes in short-duration convective storms which cover only small areas. The Snowy Mountains Engineering Corporation (1973) estimates that individual convection cells may be spaced 15–25 km apart. The present raingauge network is inadequate to sample rainfall of this type. As a result, the data used as average basin rainfall may contain huge inaccuracies. An example of this is shown in Fig. 4 using data for the Wahgi River whose basin has 14 raingauges giving coverage much better than any of the other basins. As may be seen, the model seems to give a fair reproduction of flood and baseflow events except in one case, occurring from the 4th to the 10th of October. According to records, 150 mm of rain fell on the catchment during this period and the results from the model show that a large flood occurred with a peak daily runoff of 42.5 mm. In reality, no flood occurred and for most of the time the flow was receding – suggesting that the rainfall was incorrect. Anomalies such as this occur quite frequently owing to inadequate rainfall data and are a constant problem in areas where data are limited and sampling networks are inadequate.

If random errors are present in the rainfall input to the model, it is probably better to assess model performance by examining the correlation between observed and calculated runoff using a longer time unit such as one month. This has the effect of sampling through the range of errors and averaging them out. Correlations between observed and calculated monthly runoff have therefore been calculated and are presented in Table 4. The monthly r values are considerably higher than the daily values and indicate that the model performs quite well.

Although the montly correlations between observed and calculated runoff are quite high, they give a misleading impression of the quality of model performance. The observed and calculated monthly flow hydrographs shown in Fig. 5 indicate that in spite of the high correlations, there are substantial differences between observed and calculated runoff on many of the basins. To see just how misleading the correlation coefficients are, compare the hydrograph for the Tua River with that of the Upper Gumants River. The hydrograph for the Tua River is for the model calibration period and is therefore close to the highest standard of runoff simulation which can be obtained. The observed and calculated monthly runoffs closely correspond and the r value is 0.975. On the Upper Gumants, the correlation between observed and calculated monthly runoff is 0.961 but the observed and calculated values do not correspond closely. Instead, the model seems to consistently overestimate runoff. These results suggest that the correlation coefficient is a poor index of model performance because it measures the degree of association between variables instead of their deviation from each other. It would therefore be better in future studies if workers in the rainfall–runoff modelling field would standardize on some form of dimensionless objective function as a measure of model performance such as that presented by Ibbitt and O'Donnell (1971).

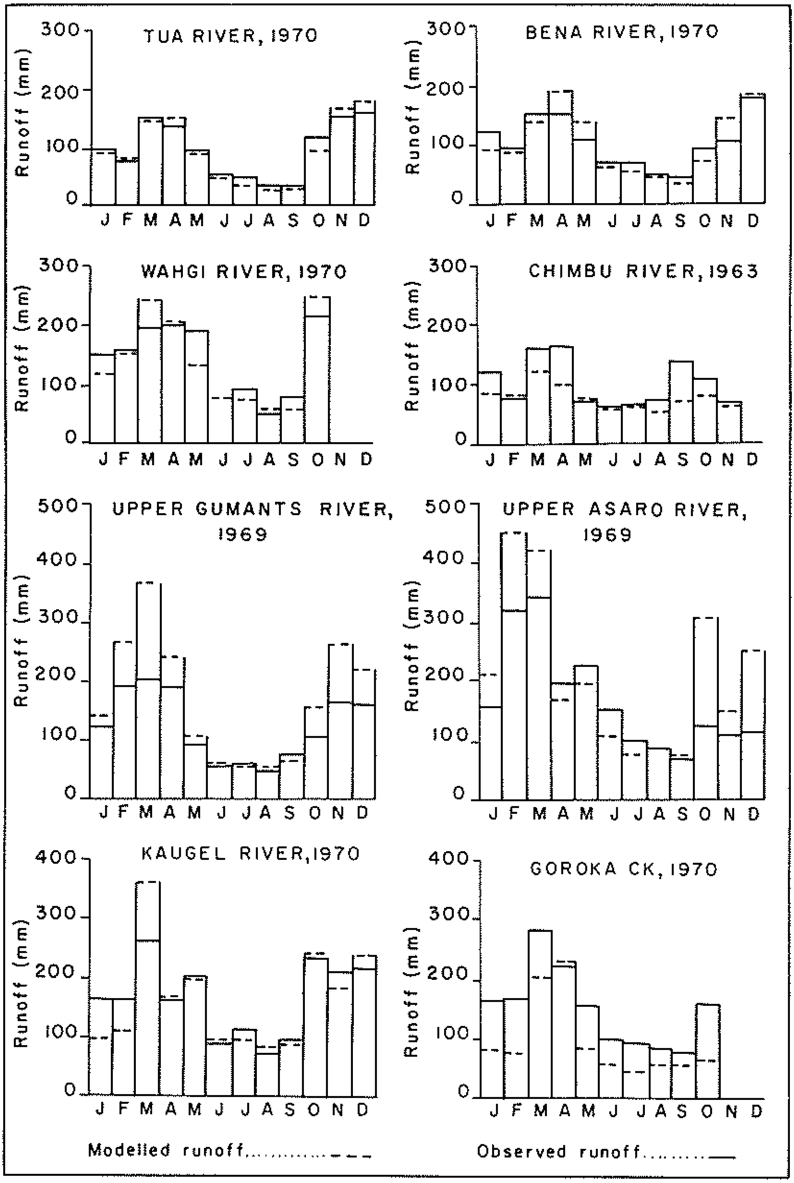

FIG. 5 – Observed and model generated monthly runoff for rivers in the Papua New Guinea Highlands.

Examination of the hydrographs in Fig. 5 indicates that some basins are modelled better than others, and on most basins the dry season runoff is reproduced more accurately than runoff during the wet season. This pattern suggests that some of the errors in the model results may be systematic rather than random. If systematic errors are present, it is better to assess model performance on a frequency basis and to compare observed and calculated flow-duration curves. This tends to remove most of the effect of random data

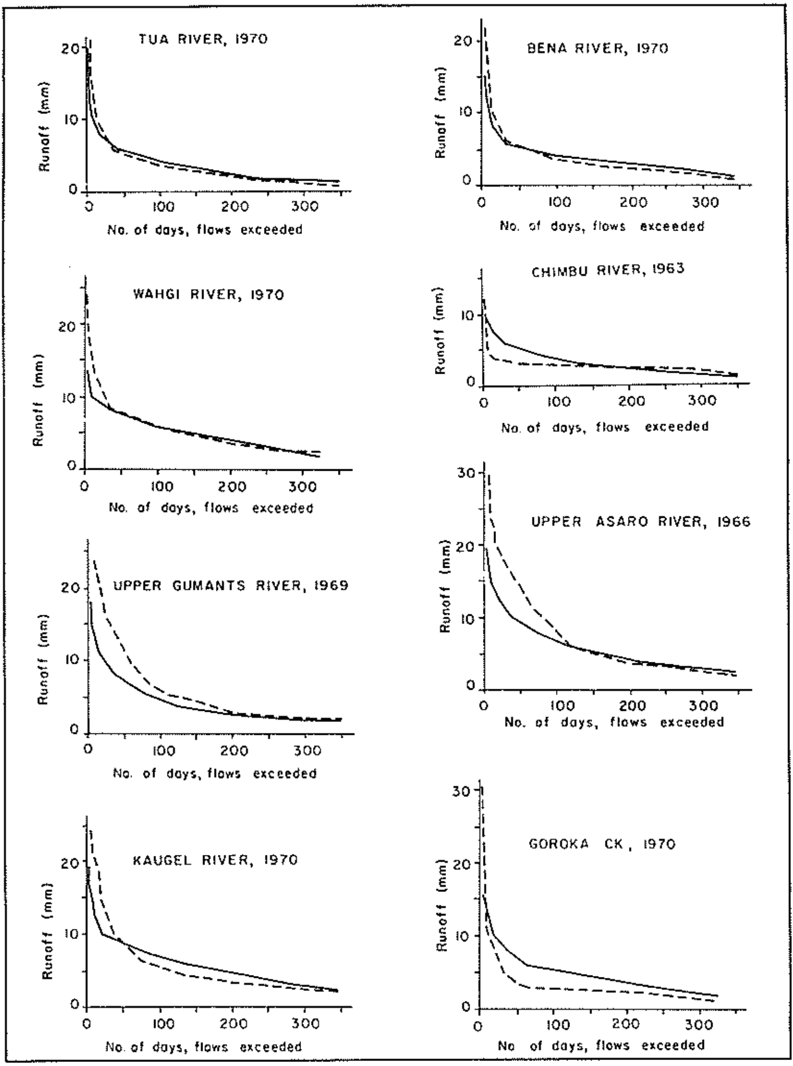

FIG. 6 — Observed and model-generated flow-duration curves for rivers in the Papua New Guinea Highlands. The solid lines represent the observed duration curves, while the broken lines show those generated by the model.

errors and gives a more reliable indication of model performance than the monthly hydrographs.

Examination of the flow-duration curves (Fig. 6) shows that the modelled basins fall into three groups.

(i) Basins in which observed and modelled flow duration is similar over most of the flow range. These basins are the Tua, on which the model was calibrated, the Bena and the Wahgi.

(ii) Basins in which the lower part of the duration curve is modelled fairly closely are the Chimbu, the Upper Gumants and the Upper Asaro.

(iii) Basins in which the duration curve is poorly reproduced over its whole range. These basins are the Kaugel River and Goroka Creek.

The basins which are modelled well both have similar characteristics to the Tua River (Table 2). The Wahgi is of a similar size to the Tua, but the Bena is considerably smaller. This suggests that it may be possible to use parameter values derived for one basin on other basins with similar characteristics but which are slightly larger or smaller. It is unlikely, however, that the transfer of model parameters could be done successfully with very small catchments, as the poor results for Goroka Creek indicate.

In the second group – basins in which only the lower part of the duration curve is reproduced well – two rivers have similar characteristics to the Tua. These are the Upper Asaro River and the Chimbu River. On the Upper Asaro, daily runoffs in excess of 6 mm are consistently overestimated, suggesting that the values of the model parameters which control flood size are incorrect. On the Chimbu River, daily runoffs between about 3 and 10 mm are underestimated while runoffs in excess of 10 mm are overestimated. This may result from the use of incorrect model parameter values but it could also be due to runoff record errors. The rating curve for the Chimbu is known to be highly unreliable because of a shifting control (P. Williamson, PNG Bureau of Water Resources, pers. comm.) so runoff record errors may be extensive. The good results for low flows on the Upper Gumants are surprising since it is a very small basin and is geologically quite different from the Tua. Presumably the good reproduction of the baseflow section of the duration curve is coincidental.

The poor results for the third group of catchments is to be expected. The Kaugel Basin is geologically quite different to the Tua Basin, while Goroka Creek has a very small catchment and substantial areas of alluvial deposits.

The flow-duration curves show that there is some potential for transferring calibrated model parameter sets between catchments. However, they also illustrate that systematic errors will occur because, on every basin, the largest flows are consistently overestimated. This may occur for three possible reasons. Firstly, all the discharge-rating curves may be in error, which is unlikely. Secondly, the paths in the model used to calculate flood flows or the parameters associated with them may be unrepresentative. This may be the case on basins where all flood flows are modelled badly. On other basins, however, smaller floods and even some large ones are modelled adequately using the same model paths and parameter values, suggesting that the model is not consistently in error. The third and the most likely possibility is that the rainfall input is in error. This is because many storms in Papua New Guinea cover small areas and produce very high point rainfalls at the storm centre. Away from the storm centre the rainfall decreases rapidly, so average rainfall over the basin may be much less than recorded rainfall. If there are only a few raingauges in a basin and one or more of them lies close to a storm centre, the measured rainfall for the basin for that particular day will be greatly overestimated. This appears to introduce a systematic error when many point rainfalls in excess of about 30 mm/day are extended to larger areas even where there are several raingauges and areal weighting of rainfall can be undertaken. It may therefore be necessary to use a point-rainfall correction factor in rainfall–runoff model studies in Papua New Guinea.

CONCLUSIONS

Using a modified version of the Boughton model, an attempt was made to examine the potential for using rainfall–runoff models on ungauged basins in the Papua New Guinea Highlands. The model was calibrated for the Tua River, and the calibrated model parameters were used to calculate runoff from rainfall for seven other basins with varying characteristics. Model performance was assessed using the correlation between observed and calculated daily runoff, the correlation between observed and calculated monthly runoff, and similarity of the observed and calculated flow-duration curves.

Correlations between observed and calculated daily runoff lay within the range 0.403–0.755; however, these values are affected by random errors in model input, so they are not the best index of model performance. Monthly runoff correlations lay within the range 0.817–0.961. These values are misleading, since systematic errors in model output exist mainly because the model has a tendency to overestimate large flows.

Probably the most effective test of model performance is to compare observed and calculated flow-duration curves. This largely removes random errors and exposes systematic errors. Comparison of flow-duration curves indicates that the same set of model parameters cannot be used on basins with dissimilar physical characteristics. On basins with similar physical characteristics, however, calibrated model parameters were transferred with reasonable success where low flows are concerned. At higher flows there is no guarantee of success although some good results were obtained.

All the runs with the model tended to overestimate the largest flows. This even occurred in the year in which the model was calibrated and on the basin it was calibrated on. Systematic errors of this type seem to result from the characteristics of the rainfall data rather than deficiencies in the model.

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