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EVALUATION OF A DIGITAL CATCHMENT MODEL ON NEW ZEALAND CATCHMENTS

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ABSTRACT

A daily version of the Stanford Watershed Model IV has been used on four experimental basins and one larger catchment in New Zealand. Sensitivity tests showed that changing the values of those model parameters describing moisture capacities and the associated recession constants did not affect the resultant simulation significantly. Optimum values of the more significant parameters, the infiltration and interflow parameters, were found to depend upon the calculation time interval as well as the catchment characteristics. A procedure for using the model on ungauged catchments in New Zealand is suggested.

INTRODUCTION

Research into digital modelling of catchment response to rainfall has been actively pursued at Stanford University, California, since 1959. In 1966 Crawford and Linsley (1966) published details of the Stanford Watershed Model IV which has been used successfully on many catchments, one recent application being to the Clyde River in Scotland (Fleming, 1970). Model V has since been developed and is used on a consulting basis in the United States.

This paper describes the application of Model IV to four experimental basins and one large catchment in New Zealand. Optimum values for the model parameters were determined for each catchment and compared with those suggested by Crawford and Linsley (1966). The sensitivity of the simulation to changes in each parameter was also investigated. Daily records were used and flows were simulated for one year. For one experimental basin a 'second optimum set' of parameters was determined from hourly data and compared with that from the daily records.

Stanford Watershed Model IV

The model operates on each hour's rainfall in turn by calculating the change in moisture content of the various sections of the hydrological cycle. Each section is represented by a container of

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a certain capacity with an outlet governed by an empirical equation. Rain not accepted by the various containers becomes overland flow. The major model components are shown in Figure 1 and briefly discussed below.

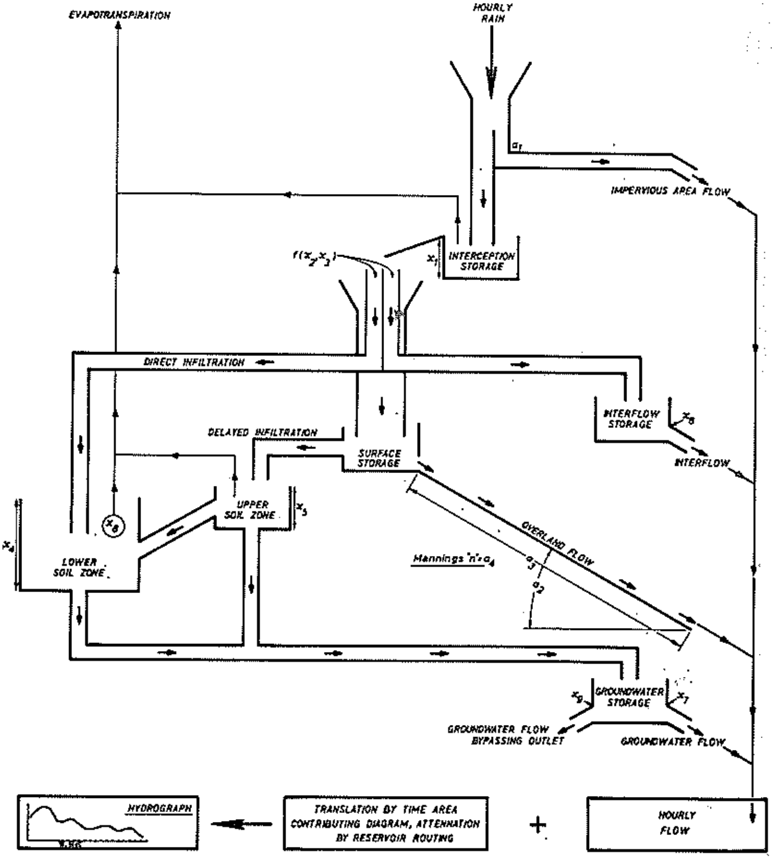

FIG. 1 — The Stanford Watershed Model IV.

A) Interception. Interception storage is represented by the overflow container. If the hourly rain fills the container the overflow is available for infiltration or overland flow.

B) Infiltration. Moisture storage in the soil is represented by three containers, the upper and lower soil containers and the interflow container. Water input to these depends upon their current content and upon a parameter which reflects the catchment maximum infiltration capacity. A fraction of the water infiltrating is diverted to the interflow container, the remainder being divided between the upper and lower soil zones.

C) Subsurface Flow. The ground-water container is fed by the soil-moisture storages. This and the interflow container discharge into the stream at a rate proportional to their contents.

D) Overland Flow. This is computed using an equivalent plane of constant slope to represent catchment topography. An empirical relation between the amount of water in the overland-flow container and the amount of water on the equivalent plane, assuming steady flow at the current inflow rate, is used to determine the unsteady outflow from the bottom of the plane. This is subtracted from the flow container and added to the stream flow.

E) Evaporation. The hourly potential evaporation is estimated from values input daily. The model attempts to satisfy the potential by removing water, first from the interception container, and then from the upper and lower soil containers.

F) Snow. Snowfall is input to a snow container from which output is determined by an energy-balance method.

G) Stream Flow. The inputs to the stream system are subject to delay by a time-area-contributing diagram to represent flow to the catchment outlet. Attenuation in the stream system is simulated by the operation of a hypothetical linear reservoir to give the hydrograph resulting from one hour's rain. Superposition of this on the flow resulting from the previous rains gives the total hydrograph.

Model Parameters

To operate the land phase of the model, estimates of 13 quantities are required. Four of these, labelled a in Figure 1, can be estimated from the physical features of the catchment. They are a mean slope, length, and roughness for the equivalent plane and the percentage of the area which is impervious. The other nine, labelled x, must be derived by comparing the flow simulated by the model with the recorded flow. Considering each in turn:

A) Interception storage capacity, x_1. This is the amount of water which can be intercepted before reaching the ground. It is therefore related to the projected leaf area of the vegetation and the capacity of the foliage to retain water. Values suggested by Crawford and Linsley (1966) are 0.1 to 0.2 inches (0.25–0.50 cm).

B) Interflow and infiltration factors, x_3, x_2. These determine the distribution of water between soil storage, prompt subsurface flow (interflow) and overland flow. Soils with high vertical permeability will allow rapid infiltration (high x_2) and soils with high horizontal permeability will allow rapid interflow (high x_3). Crawford and

Linsley suggest that x_2 should lie between 0.3 and 1.2 inches (0.75–3.00 cm) and x_3 between 0.5 and 3.0.

C) Lower and upper soil factors, x_4, x_5. These determine the moisture-holding capacity of the model and could be described by the saturated moisture contents in the surface and subsurface layers. According to Crawford and Linsley, x_4 is $4 + (\frac{1}{4}$ to $\frac{1}{8})$ times the mean annual rainfall in inches and x_5 ranges from $0.06x_4$ to $0.14x_4$ depending on catchment slope and vegetation and on the depression storage.

D) Interflow and ground water daily recession constants, x_6, x_7. These may be connected with the permeability/moisture-content relation in the horizontal direction. They lie between 0 and 1.

E) Lower soil evaporation factor, x_8. This depends on the heat absorption and conduction properties of the soil and on the soil-suction/moisture-content behaviour. Since potential evaporation can usually be satisfied from the upper soil and interception containers, x_8 can often be assumed to be zero.

F) Ground water bypass fraction, x_9. This is the fraction of the ground water which does not become stream flow before the outlet; it depends upon the subsurface geology of the catchment outlet and on the ground water flow rate. Values range from 0 to 1.

TABLE 1 — Summary of catchment data.

Catchment	*Area acres (km²)*	*Average slope*	*Vegetation*	*Mean elevation ft (m)*	*Location*
Moutere 14	10.7 (0.04)	0.31	Improved pasture	338 (100)	Nelson
Moutere 5	17.2 (0.07)	0.31	Improved pasture	402 (120)	Nelson
Taita 2	27.0 (0.11)	0.58	85% scrub 15% regen. native forest	428 (130)	Wellington
Makara 11	19.4 (0.08)	0.54	Weedy pasture	510 (160)	Wellington
Upper Taieri	185,000 (740)	0.05	Tussock grassland	2800 (850)	Central Otago

CATCHMENTS

The model was used on five catchments, the characteristics of which are summarized in Table 1. One large catchment (Upper Taieri) was included to ensure that the conclusions drawn from this study were not related solely to small catchments. Data for these catchments were drawn mainly from N.Z. Ministry of Works (1968, 1969).

Moutere 14 and Moutere 5

The Moutere experimental catchments are situated 16 miles (26 km) south-west of Nelson City, South Island. The soils are central yellow-brown earths and vegetation consists of improved pasture (perennial ryegrass, white clover and subterranean clover). The land is hard grazed with sheep and cattle with spells for recovery. A 2-foot (61-cm) H-flume and a daily Kent recorder are used for flow measurement. Moutere 5 has one automatic and five manual rain gauges while Moutere 14 has eight manual gauges.

Taita 2

Taita 2, another experimental catchment, is 10 miles (16 km) north-west of Wellington on moderately weathered yellow-brown earths. Vegetation cover consists of 85% scrub (manuka and gorse) and 15% regenerated native forest (hard beech and kamahi) in the gullies. A 90° V-notch and a weekly Lea recorder monitor flows, and rainfall records are obtained from the automatic rain gauge at the Taita climate station just outside the catchment.

Makara 11

The Makara 11 experimental catchment is 12 miles (19 km) west of Wellington with central yellow-brown soil. Pasture is weedy and open, consisting of browntop and sweet vernal. The land is lax grazed in summer and hard grazed in winter. There are two manual rain gauges, an automatic rain gauge and a three-foot (91-cm) H-flume with a daily Kent recorder.

Upper Taieri

Upper Taieri has an area of 289 square miles (740 km^2) in Central Otago, a low-rainfall area in the South Island. The soils are a shallow-weathered material derived from the underlying schist which frequently outcrops. The land is covered mainly by tussock with improved pasture near the river. It is used for grazing sheep and cattle.

USE OF THE MODEL

General

The original program, written in ALGOL by Crawford and Linsley, was rewritten in FORTRAN for use on the IBM 360/44 computer at the University of Canterbury. The 64K core storage could hold one year's daily data, and execution took about $1\frac{1}{2}$ minutes per year of data. Input to the program can be listed as:

(i) Control factors to specify calculation time and type of output;

(ii) Model parameters to typify the catchment (the *x*s discussed above);

(iii) Climate — rainfall during each time interval and daily potential evaporation;

(iv) Initial conditions — amount of water in each container at the start.

A calculation time increment of one hour as used in the Stanford model was, in general, unsuitable because hourly rainfall and stream-flow data are not extensive in New Zealand. Further, it was expected that the magnitude of the increment would influence the accuracy of the simulation. There would, therefore, be an optimum increment dependent upon some measure of the catchment response time, e.g. the time-lag between the start of a storm and the first measurable change in flow at the gauging station. Thus, in rewriting the program, provision was made for performing the calculations any required number of times per day allowing the accuracy attained by, e.g. hourly and daily simulation to be compared.

The snow section of the model was omitted because the temperature data required were not available. The stream flow part was not included because of the small sizes of most of the catchments.

Parameter Optimization

The parameter set which resulted in the most accurate simulation was considered to be the optimum set. The peak flows were matched first and then the total simulated flow volume adjusted to match the recorded flow volume as closely as possible without unduly disturbing the matching of the peak flows. Three methods were used to determine the required set.

A) Optimization by trial and error, judging the goodness of fit by graphical inspection. This was slow, and visual estimation of goodness of fit is not objective. It is also unsuitable for automatic computation.

B) Determination of the sensitivity of the simulated flow to changes in each of the parameters. Optimization by using these results to deduce better parameters, judging the goodness of fit by inspection. Values quoted in this report were obtained by this method which has the same defects as method A above. It does, however, give considerable information as to the effect of each parameter. This is illustrated in Table 2.

TABLE 2 — Sensitivity of simulated hydrograph to changes in the parameters x_i for Moutere 5.

Parameter		*From*	*To*	*Effect on peaks*	*Effect on total volume*
Interception storage capacity	x_1	0.1	0.2	−(0 to 5%)	−10%
Lower soil zone infiltration factor	x_2	1.0	3.0	−(10 to 50%)	−30%
Upper soil zone infiltration factor	x_3	1.5	4.5	+(0 to 20%)	+40%
Lower soil zone factor	x_4	10.0	50.0	−(0 to 10%)	−10%
Upper soil zone factor	x_5	1.0	11.0	0	0
Interflow daily recession constant	x_6	0.5	0.2	+(10 to 20%)	0
Ground water daily recession constant	x_7	0.95	0.45	+(0 to 50%)	+40%
Lower soil evaporation factor	x_8	0.28	0.38	0	0
Ground water daily bypass fraction	x_9	0.50	0.80	0	− 5%

C) Automatic optimization of a numerical index of goodness of fit. The sum of the square of the deviations between the daily recorded and simulated flows for a year's record was used as the index. The method of steepest descent and a minimization method which worked on one parameter at a time were used as optimizing methods. The former is an automatic form of method B. Both methods reduced the sum of the squares of the daily flow differences, but the theoretically better hydrographs were judged to be worse by inspection. The low flows seemed to be exerting too much influence at the expense of the peaks. Further study using the fourth power of the differences is intended.

PRESENTATION AND DISCUSSION OF RESULTS

Sensitivity Tests

Table 2 shows two of the effects produced on the simulated hydrograph by changes in each of the model parameters x_1 to x_9 for Moutere 5. Hydrographs from the other catchments were affected by parameter changes in the same way and to approximately the same degree as for Moutere 5. There were, however, two exceptions which remain unexplained. On the large catchment (Upper Taieri) increasing x_4, the lower soil zone factor, had the effect of decreasing the peaks, and on Taita 2, increasing the interflow factor x_3 decreased the peaks. Parameters not under investigation were held at values near optimum as determined by trial and error (see method A) while the remaining parameter was varied. It is necessary to give a range for the effect on the peaks because not all peaks in a given record were affected to the same degree. Changes in total volume reflect changed storage in, and losses from the model.

The sign of the effects on the peaks and on the total volume shown in Table 2 are in accord with predictions that would be made based on physical reasoning. For example, a decrease in peak flows for an increase in x_2 and an increase when x_3 is increased reflects the influence of delayed versus rapid runoff. The large effects produced by changes in x_2 and x_3 demonstrate the importance of distributing the water reaching the ground correctly among the several possible ways of reaching the stream. A good knowledge of ground conditions in the catchment will therefore be essential. The interflow daily recession constant is also shown (Table 2) to be important for its effect on the peaks but, surprisingly, it has no effect on the total volume.

Parameters with no noticeable effect were the upper soil zone container parameter x_5 and the lower soil evaporation factor x_8. It is surprising that x_5 had no effect. A possible explanation is that x_5 is physically dependent upon x_2 and x_4 and, of the three, hydrologically of least importance. With x_2 and x_4 constant, any changes in the simulated flow consequent on changes in x_5 alone may have been undetectable.

Best Parameters (Daily Values)

The best parameter set was derived on a daily basis for each catchment using the sensitivity information described above. Table 3 lists the result together with values suggested by Crawford and Linsley. For the Moutere catchments and for Makara 11 the agreement is good. However, for Taita 2 x_2, and for Upper Taieri x_2 and x_3, both important parameters (see previous section), are outside the indicated ranges. With x_3 being 5.0 rather than 3.0, the maximum suggested value, the effect on the peaks would be, from Table 2, approximately $+10\%$ and that on total volume approximately $+25\%$.

Crawford and Linsley (1966) emphasize that x_2, x_4 and x_5, being interrelated, will be difficult to estimate and must be found

TABLE 3 — Best parameter sets.

Parameter	*Moutere 14*	*Moutere 5*	*Taita 2*	*Makara 11*	*Upper Taieri*
Interception storage capacity x_1	0.1 (0.10)	0.1 (0.10)	0.15 (0.15)	0.15 (0.15)	0.10 (0.10)
Lower soil zone infiltration factor x_2	1.0 (0.3–1.2)	1.0 (0.3–1.2)	2.0 (0.3–1.2)	1.0 (0.3–1.2)	3.0 (0.3–1.2)
Interflow infiltration factor x_3	1.77 (0.5–3.0)	1.5 (0.5–3.0)	3.0 (0.5–3.0)	3.0 (0.5–3.0)	5.0 (0.5–3.0)
Lower soil zone factor x_4	9.07 (9–14)	10.0 (9–14)	10.0 (10–16)	10.0 (10–16)	10.0 (8–12)
Upper soil zone factor x_5	1.0 (0.7–1.1)	1.0 (0.7–1.1)	1.0 (0.7–1.1)	1.0 (1.4–2.2)	1.0 (0.6–1.0)
Interflow daily recession constant x_6	0.8	0.5	0.75	0.3	0.75
Ground water daily recession constant x_7	0.98	0.9	0.93	0.98	0.98
Lower soil evaporation factor x_8	0.23 (0.23)	0.26 (0.23)	0.26 (0.28)	0.26 (0.28)	0.26 (0.23)
Ground water daily bypass fraction x_9	1.01	0.5	1.0	0	1.0

Values in brackets are given as guides by Crawford and Linsley (1966).

by comparison of recorded and simulated flows. The present results bear this out and suggest that the values of Crawford and Linsley be used only as initial guesses. The model may thus have limited use in ungauged catchments.

Changes in many of the parameters were found to affect the simulated hydrograph in several ways simultaneously. A particular change may increase the peak flows while altering the speed of recession and affecting the total volume. This tendency made it difficult to fit a flow record satisfactorily in all respects. Further, no one parameter was able to increase the later peaks in a sequence more than the earlier ones. Figures 2 and 3 show that such a parameter was needed in this study. Hence the model, in spite of its large number of parameters, did not appear sufficiently versatile for accurate simulation.

It is to be noted that the values given in Table 3 were obtained by reproducing the peak flows at the expense of matching the flow volumes. Doing the reverse may have produced a significantly different set of parameters. This has not yet been investigated.

Achievement of optimum peak flow prediction resulted in simulated flow volumes being too high in all cases. Adjustment

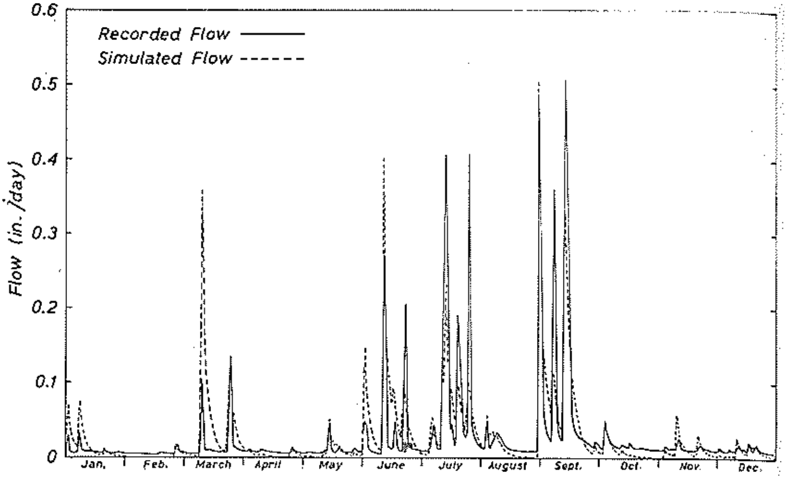

FIG. 2 — Recorded and simulated flows, Taita 2 catchment, 1964.

of the volumes to within 50% reduced the accuracy of the peak simulation. Consequently for all simulated hydrographs any given peak flow could only be guaranteed to +100% and −50%, these figures referring to the maximum discrepancy occurring during the years simulation (see Fig. 2). Table 4 lists the error in the yield and the correlation between actual and simulated flows for each catchment. Correlations by Crawford and Linsley range from 0.94 to 0.99 for, usually, records of six to eight months duration.

TABLE 4 — Correlation and yield error for simulated flows.

Catchment	*Year*	*Correlation*	*Yield error (% recorded flow)*
Moutere 14	1965*	0.88	+ 10
Moutere 5	1963*	0.59	+ 30
Makara 11	1965*	0.79	+ 50
Taita 2	1964*	0.79	+ 5
Taita 2	1965	0.82	+ 15
Upper Taieri	1917*	0.74	+ 30
Upper Taieri	1918	0.05†	+ 35
Upper Taieri	1919	0.56	+100

* denotes year of parameter derivation.

† appears to be erroneous flow information.

As an arbitrary standard for judging a good simulation, one may say that the error in predicted peak flows should exceed 25% of the recorded peak no more than once a year, and the total flow error should not exceed 25%. By this standard the results of daily simulation were not good.

Two catchments were simulated for periods other than those used to derive the parameters. The results are shown in Table 4 and Figure 3.

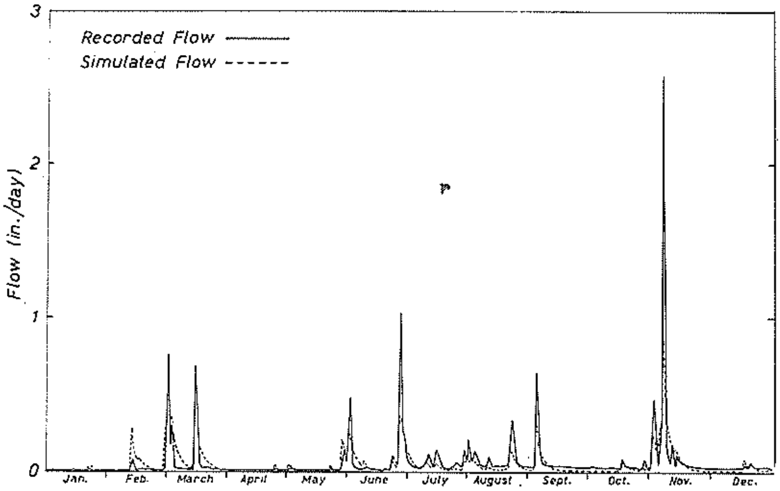

FIG. 3 — Recorded and simulated flows, Taita 2 catchment, 1965.

Effect of Calculation Time

Hourly records, available for Moutere 5, enabled the time-interval dependence of the optimum parameters to be investigated. An improvement in the accuracy of the simulation was noted. Although the reduced calculation time interval was expected to give greater accuracy, this could have been due to the shorter time interval (46 days) and thus fewer peak flows used to derive the parameters.

The optimum hourly parameters are shown together with daily values in Table 5. The infiltration parameter x_2 required a quite different value, viz. 0.0, for hourly simulation and is outside the range suggested by Crawford and Linsley. A zero value for x_2 implies no direct infiltration and no flow to the interflow storage which is governed by the product x_2x_3. It is thought that by calculating on an hourly basis, and thus allowing greater opportunity for moisture distribution throughout the model, the need for the artificial distribution imposed by x_2 and x_3 is removed for the Moutere 5 catchment. Changes in the ground-water constants x_7 and x_9 for hourly simulation are probably also linked with the more frequent distribution of water throughout the model.

TABLE 5 — Best parameter sets for daily and hourly simulation on Moutere 5.

Parameter	*Daily*	*Hourly*
x_1	0.1	0.1
x_2	1.0	0.0
x_3	1.5	1.5
x_4	10.0	10.0
x_5	1.0	1.0
x_6	0.5	0.5
x_7	0.9	0.43
x_8	0.26	0.26
x_9	0.5	0.3

The parameters x_1 and x_8 are unrelated to the calculation time and remain unchanged. It is difficult to predict whether or not x_4 and x_5 should change and in this particular example they did not. Since it is the product x_2x_3 which governs the interflow, x_3 cannot effect the simulation when x_2 is zero. Also, with no interflow the result is independent of x_6. The constancy of x_3 and x_6 is not proven by these results.

CONCLUSIONS

The parameters derived for daily simulation in New Zealand generally agreed with those found in the United States. However, the differences that occurred in the key infiltration parameters were sufficient to indicate that reliable use of the model will be achieved only by matching recorded and simulated flows. Performance of the model on a daily basis was disappointing and hourly simulation proved more accurate, but with a different set of model parameters. The Stanford Watershed Model IV will thus be of use in New Zealand for simulation, at least to the accuracy reported herein, on gauged catchments.

For ungauged catchments the model could be of use if the parameters can be estimated in some way without recourse to recorded flows. The following procedure is proposed:

(i) Choose a standard time interval (a day or an hour) so that parameter comparisons can be made.

(ii) Obtain the best parameter set using, say, three years flow records for each of the representative basins in New Zealand.

(iii) Seek correlations between these parameters and measurable catchment factors such as topography, percentage forest, and soil type.

(iv) If (iii) fails, the representative basins will have to be assumed sufficiently representative to enable parameters derived in them to be used in other basins which they represent.

(v) Using (iii) or (iv) prediction of flows in the ungauged catchment may be attempted.

This study has suggested ways in which the model may be improved. Among these are:

(i) Improvement in the versatility of the parameter set.

(ii) Reduction in the number of parameters, if this does not prove to be contradictory to (i).

(iii) An increase in physical relevance.

These can only be achieved when a fuller understanding of the relevant hydrological processes is gained. A possible starting point would be the replacement of the subsurface model components by a solution of the unsteady unsaturated flow equations. Freeze (1969) has published such a solution. This is being incorporated into the model by the writers in an attempt to effect the improvements mentioned above.

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