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A MODIFIED CATCHMENT MODEL OF THE UPPER TAIERI RIVER, OTAGO, NEW ZEALAND

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ABSTRACT

Most digital simulation models reported in the literature have been applied to situations which are very suited to analysis by these general models, such as those developed by Crawford and Linsley and by Boughton, and where sufficient data have been available.

Since for many practical purposes it is not possible to have data which are ideal for use with mathematical catchment models, for example where conditions are not ideal or where available data are restricted, it is a useful exercise to determine whether the type of data commonly available can be usefully employed in a model. These conditions can be found in the Upper Taieri River catchment, Otago, which possesses the disadvantages, as far as digital simulation is concerned, of its size of 233 square miles, its varied physical and hydrological characteristics and its lack of adequate data.

In this test the model developed by Boughton is modified to suit the particular conditions and the results compared with recorded river flow data.

Estimating runoff from rainfall by a simple correlation and regression, taking the data month by month, gives results of limited value in this area. Using the modified model to predict runoff, the correlation is increased for all months except two. The exercise has shown that even when the data are far from ideal, it has been worthwhile to develop and use a mathematical catchment model for the prediction of runoff, as this has proved rather more useful than the simple methods. However, in this instance the final results, so far, fall short of what is desired for water resources assessment purposes.

INTRODUCTION

Crawford and Linsley (1966), in establishing criteria for hydrological models, suggest that: "the model should represent the hydrological regimens of a wide variety of streams and rivers with a high order of accuracy". While this is a desirable objective, it is often the case that particular physical conditions of a catchment or peculiarities in the data available call for modifications

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in the application of the general models such as those developed by Crawford and Linsley, and by Boughton (1965, 1968).

Most digital simulation models reported in the literature have been applied to situations which are very suited to analysis by these general models, and where sufficient data have been available. Crawford and Linsley (1966) describe the application of their model mainly to experimental basins, where – for example – precipitation data were available at 15-minute intervals, where the catchment area is small (although they have also produced excellent results with large areas), and where there are few physical peculiarities.

It is of interest, therefore, to consider whether digital simulation models can be applied successfully to conditions which are not ideal, and where the available data are very much restricted.

These conditions can be found in the Upper Taieri catchment, which possesses the disadvantages, as far as digital simulation is concerned, of its size of over 200 square miles, its varied physical and hydrological characteristics, and its lack of adequate data.

In this test the model developed by Boughton (1965, 1968), which is the only one which has had extensive application in New Zealand, is modified to suit the particular conditions, and the results compared to recorded river flow data.

DESCRIPTION OF THE CATCHMENT

The Upper Taieri catchment encloses 233 square miles, being the area above the Paerau Bridge gauging station (Fig. 1) approximately 40 miles inland from Dunedin, in a north-westerly direction, on the east coast of the South Island of New Zealand.

The catchment is bounded to the west by Rough Ridge, to the east by the Rock and Pillar and Lammermoor Ranges, to the south by the Lammerlaw Range, and to the north by a low ridge of schist basement rock separating the Styx Basin from the extensive Maniototo depression. The area is one of accentuated relief, combining areas of swampy and poorly drained land around the Taieri River within the Styx Basin and surrounding deeply dissected hills and the Lammerlaw Plateau. Elevations range from 3,973 ft at Lammerlaw Top to 1,815 ft at the Paerau gauging site, with a mean catchment elevation of 2,807 ft.

Geologically, the catchment forms one of a series of fault-angled depressions with associated characteristic block features, and plunges north-east from the high schist plateau of the Lammerlaw Range anticline. The basement rocks of the Styx Basin and

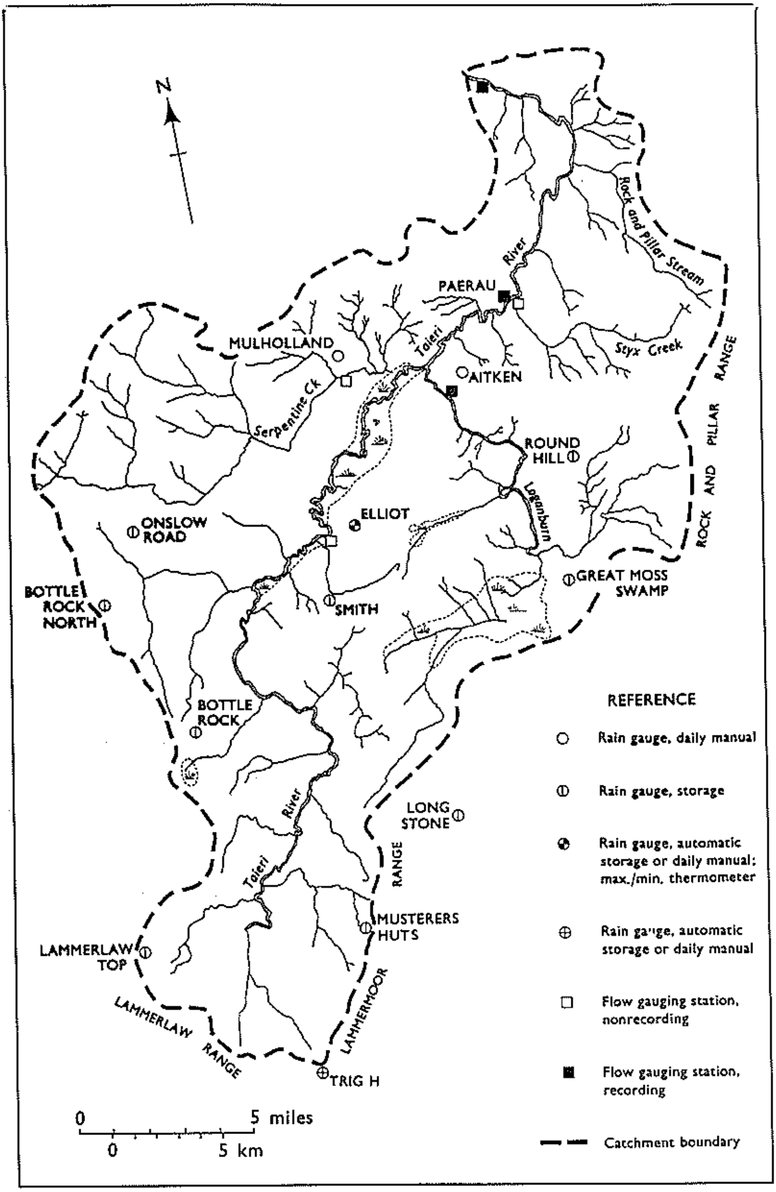

FIG. 1 — Map of the Upper Taieri River catchment.

surrounding catchment are of the Haast schist group chlorite Subzone 4, with the present depressions comprising the Styx Basin and Great Moss Swamp subsequently infilled with Pleistocene and Recent gravels and swamp deposits. The post-Pleistocene landscape has evolved under semi-arid climatic conditions, and the streams of the area are generally underfit and consequent on the deformation. Because of the gentle gradients on the floor of the Styx Basin, free meandering bends and ox-bow lakes are common with the Taieri River, bringing with them associated problems of unknown channel and surface storage during periods of higher flows and hence regulation to an unknown degree of both surface and subsurface outflows.

The soils of the Upper Taieri fall predominantly into the yellow-grey and yellow-brown groups with the area above the low-lying Styx Basin predominated almost entirely by the yellow-brown Teviot and Dunstan soils (together covering 70.4% of the area). At lower altitudes yellow-grey Arrow, Pukerangi and Blackstone soils predominate (together covering 16.1% of the total area), with associated areas of recent gley and organic soils on the flood plain of the Taieri River.

Indigenous vegetation associations occurring in the Upper Taieri have been identified as low-altitude fescue tussock grassland, low-altitude silver tussock, red tussock, high-altitude blue tussock, alpine cushion, alpine bog, alpine herbfield, swamp vegetation and subalpine scrub. These communities have been divided into categories of supposed hydrological similarity; e.g., silver and hard tussock are classed as short tussock, snow and red tussock as tall tussock. Apart from the mixed short and tall tussock association, the distribution of the remaining communities is due to a combination of altitude and exposure factors and drainage. The mixed short and tall tussock is undoubtedly expanding, owing to the activities of man, with snow tussock communities being degraded into mixed snow and hard tussock, or even pure hard tussock following repeated fires at altitudes below 2,500–3,000 ft. At higher altitudes, where hard tussock is not present, snow tussock which has been killed by overburning and grazing is replaced by less palatable celmisia, resulting in tall herbfields. The extensive scabweed semi-desert vegetation which occurs in other parts of Central Otago is essentially absent from the catchment. Climatically, the Upper Taieri catchment is – broadly speaking – an area of extremes, with high temperatures in summer and strong desiccating winds common also during this period. During late autumn, winter and early spring low temperatures prevail, and very severe frosts occur frequently and often persistently. Thick surface ice on all stream channels including the main river is common during winter, thus hampering field work in the area, as does snow, which can cover even the lowest parts of the area to a depth of several inches. Snowdrifts on the upper areas can severely limit access to these regions for up to four months of the year.

Up to 1966, records of precipitation and stream flow were relatively sparse in the area and limited to daily precipitation records at Paerau for the period 1908–40 and daily flow records for the Taieri River at the Paerau gauging site for the periods 1912–13, 1916–28, 1936–39, part of 1940, 1941–44 and 1947–50 (a total of 28 years of discharges taken from daily staff gauge records).

Since 1966, flow records within the area have been substantially improved with the establishment of a series of gauging stations on the main river and tributaries and automatic recorders at Paerau and Hore's Bridge (downstream of the Paerau gauge) on the Taieri River and on the Loganburn.

A survey of historic and current precipitation and flow data for the catchment shows in broad terms that the average catchment mean precipitation is of the order of 37 inches and over the period of record varies between 18 inches (1939) and 57 inches (1919).

For the Paerau gauging site, an average annual discharge over the period of record is calculated as 288 cusecs, and on a monthly mean basis varies between a minimum of 21.3 cusecs for March 1920 and a maximum of 1,322 cusecs for September 1939. These results may, however, be subject to some error as they are derived from daily stage records and corrected historic rating curves. Seasonal mean flows also show a marked yet consistent variability and are calculated over the period of record as: spring (September to November), 450 cusecs; summer (December to February), 175 cusecs; autumn (March to May), 229 cusecs; winter (June to August), 293 cusecs; October to March, 248 cusecs; January to March, 150 cusecs.

THE BOUGHTON MODEL

Boughton's (1965, 1968) original model was designed for 'small' catchments, with likely application to the problems of agricultural hydrology, particularly for the design of farm dams and for water management. Basically, the model consists of four main stores (Fig. 2);

(a) *The interception store* (CEPMX), representing interception by vegetation. The volume of water in store (CEP) depends on the precipitation and evaporation:

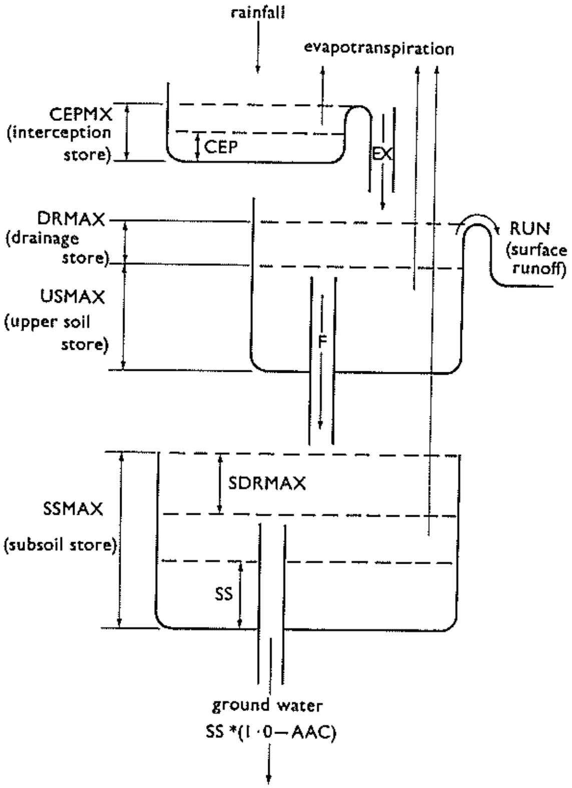

FIG. 2 — Structure of the original model.

i.e. $$\mathrm{CEP}=\mathrm{CEP}+\mathrm{RAIN}\ (\mathrm{J,M})$$

11 $$\mathrm{CEP}=\mathrm{CEP}-\mathrm{EVAP}\ (\mathrm{M})$$

subject to the upper (CEPMX) and lower (0) limits not being exceeded.

(b) *The drainage store* (DRMAX), representing the capacity of depression storage. Water enters this store if there is an excess (EX) of rainfall after the interception store and upper soil store have been satisfied

$$\mathrm{DR}=\mathrm{DR}+\mathrm{EX}$$

Water leaves this store in one of two ways.

(i) If the water in the drainage store exceeds the maximum capacity (DRMAX), the excess is divided by the subroutine RATE into the surface runoff

$$\mathrm{RUN} = \mathrm{EX} - \mathrm{F} * \mathrm{TANH}\,(\mathrm{A}),$$

and infiltration into the subsoil store (SSMAX);

(ii) The water remaining in the store (DR, DR$\leqslant$DRMAX) passes into the subsoil store (SSMAX) in daily increments,

$$\mathrm{DR} = \mathrm{DR} - \mathrm{F}$$

according to the normal exponential infiltration equation in the subroutine RATE,

$$\mathrm{F} = \mathrm{FC} + (\mathrm{FO} - \mathrm{FC})\ /\ \mathrm{EXP}\ (\mathrm{AAK} * \mathrm{SS}).$$

(c) *The upper soil store* (USMAX), representing part of the soil moisture storage. Water enters the store if there is an excess after precipitation has satisfied the interception store

$$\mathrm{US} = \mathrm{US} + \mathrm{EX}$$

Water leaves the store according to the evaporation rate

$$\mathrm{US} = \mathrm{US} - \mathrm{PCUS} * \mathrm{FUNCT}\ (\mathrm{US}, \mathrm{USMAX}, \mathrm{H}, \mathrm{EP})\ /\ 100.0.$$

FUNCT is a simplification of curves of actual evapotranspiration – soil moisture relationships produced by Denmead and Shaw (1962) and Slatyer and Denmead (1963), in which actual evapotranspiration increases linearly as soil moisture increases from wilting point

$$\mathrm{POINT} = \mathrm{H} * \mathrm{SMLEV} / \mathrm{SMMAX}$$

which is equivalent to

$$\mathrm{FUNCT} = \mathrm{ET} = \mathrm{H} * \mathrm{US} / \mathrm{USMAX}$$

until a plateau is reached depending on the potential evapotranspiration (H).

(d) *The subsoil store,* being the other part of the soil moisture storage which governs the daily loss rate. Water enters the store by infiltration from the drainage store

$$122\ \mathrm{SS} = \mathrm{SS} + \mathrm{F}.$$

Water is lost by evapotranspiration

$$\mathrm{SS} = \mathrm{SS} - (100.0 - \mathrm{PCUS}) * \mathrm{FUNCT}(\mathrm{SS}, \mathrm{SSMAX}, \mathrm{H}, \mathrm{EP}) / 100.0$$

and by loss to ground water

$$\mathrm{SS} = \mathrm{SS} * \mathrm{AAC},$$

but only if the subsoil moisture level is above a minimum value (SDRMX)

$$92\ \mathrm{IF}(\mathrm{SS} - \mathrm{SDRMX})\,120,120,93.$$

In the modified model, this limitation is changed and the above statement does not appear in the modified programme. It will be seen that the loss to ground water (SS * (1.0 - AAC)) is not considered further; thus a major modification is to include a ground water storage, which contributes eventually to runoff. This is made necessary because the Upper Taieri catchment is considered to be 'large'.

MODIFICATIONS TO THE BOUGHTON MODEL*

Areal Variations in Precipitation

The precipitation data available for the test duration of 1916 to 1927 consisted of daily manual gauge readings for Paerau. It is obvious that there would be systematic errors due to this one gauge not being representative of the whole area, even with a uniform storm, because of altitudinal and other topographic effects. There would also be random errors due to variations of intensity within storms, and when the areal extent of storms was less than the size of the catchment, and errors due to the precipitation occurring at various times and at various altitudes as snow.

Three methods were used to reduce the systematic error. Firstly, on the assumption that topographic altitude was the principle cause of systematic variation of precipitation over the catchment, the altitude of the rain gauge at Paerau was compared to the mean altitude of the catchment and a correction factor applied based on the calculations of Hutchinson's (1968) precipitation-altitude relationships. Secondly, a network of gauges was set up in the area and the results of a limited period of 18 months compared with the results from the single gauge. Thirdly, the 10-year totals of water input and water output were compared and the precipitation adjusted by a factor to give a balance.

Consideration of the three methods gave a value for a multiplying factor for the precipitation input of 1.08.

401 RAIN (K,J) = 1.08 * RAIN (K,J)

It was not possible to take into account the random areal variations in rainfall, and it is considered that much of the error in the prediction of runoff is due to this cause.

The effect of precipitation falling in the form of snow is to provide a further storage on the surface of the ground, and this was taken into account on a monthly basis by a regular monthly adjustment to the upper soil store.

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* See also Appendix 1 for modified computer program.

$$USMAX = USMAX * C(M)$$

This adjustment was calculated by balancing the calculated and actual runoff values for like months, i.e., for all Januaries, all Februaries, etc. However, this did not account for the variations in precipitation form within months, which is an important source of error, since – for example – the passage of a warm front during winter not only causes a heavy rainfall, but also causes melting of the lying snow, with a consequent high peak flow. It was not possible to overcome this difficulty by using daily weather records, as these were not available. The importance of this error is perhaps shown by a consideration of results, since 20% of the sum of the squared errors is contributed by two individual September months.

The large size of the catchment has implications concerning the mean areal infiltration rate. Fenwick and Kingston (1968) considered that in their test area, Northern Australia, rainfall occurs mostly as short-duration showers, with the implicit assumption of a dry period between showers. These dry periods allow the infiltration capacity to recover, thus allowing more water into storage, and less into surface runoff, than would be the case with continuous rain.

These authors therefore divided heavy storms into an initial lot of 1.5 inches and lots of 1.0 inch thereafter. The actual procedure for storms over 1.5 inches is to have the excess (FALL) dealt with in the infiltration-stage statements 130 to 134, after most of the day's calculations had been done for the initial 1.5 inches. Since daily falls of over 1.5 inches are quite rare in the Upper Taieri, it was considered likely that, when recorded, the gauge would be overcatching compared with the mean for the whole area. Since the infiltration capacity decreases as soil moisture increases, this overcatching causes the infiltration capacity over the whole basin to be underestimated. The division of heavy rainfall allows the infiltration capacity to recover between each lot, thus giving a better estimate of the mean infiltration capacity over the whole basin. Less of the excess water goes into surface runoff, thus bringing the computed highest peaks into line with the actual highest peaks.

Interchange Between Upper Soil Store and Subsoil Store

As shown diagrammatically in Fig. 3, the upper soil store (USMAX) represents that part of the soil moisture capacity of the soil which can immediately accept precipitation which is

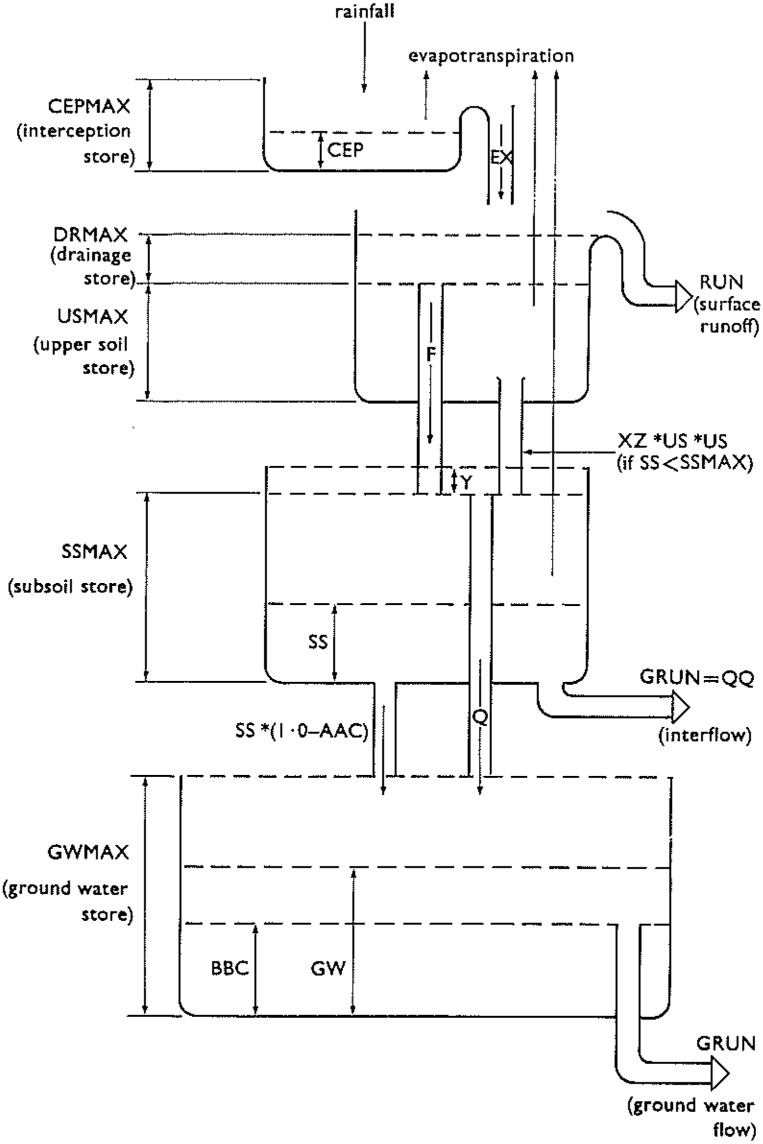

FIG. 3 — Structure of the revised model.

not intercepted (EX). When this store is overflowing (US> USMAX), then surface depression storage occurs, as does flow into the subsoil store (SSMAX), which represents that part of the moisture capacity of the soil which governs the flow into ground water (statements 13 to 226). In the original model there is no direct flow between the upper and subsoil stores, nor is there any flow out of the subsoil store when the water in this store (SS) falls below a level of (SSMAX - SDRMX). In the modified model, interflow as explained below occurs, as does evapotranspiration, so that after a dry spell the water content in the subsoil store (SS) can be greatly reduced, while the water in the upper soil store (US) is only being reduced slowly, owing to evapotranspiration. Hence a condition may arise in which the soil is too dry to provide much interflow or movement to ground water, yet too wet to allow much precipitation into it. Since this is an impossible situation, it is necessary to transfer water from the upper to the lower soil store, and so keep them in balance. Because the upper soil store and subsoil store are not strictly separate physical entities, there is no theoretical relationship to apply to this water transfer, and the relationship used was selected partly after trial and error and partly from the following consideration. Interflow, which can be considered to occur in a direction towards the streams at a slight angle below the horizontal, depends on the water in the subsoil store (SS). Movement occurs partly by capillary attraction, when the soil is quite dry, and partly because of the combined effect of hydraulic head and gravity, especially when the soil is wet or saturated. Capillary movement is very much slower than the other two causes, so that interflow occurs at a greater than proportional rate to the moisture in the soil as the moisture increases, hence movement from the upper to subsoil stores should be correspondingly at a greater than proportional rate.

It was therefore decided that the movement between the two stores should be proportional to the square of the water in the upper soil store (XZ * US * US), the proportionality constant (XZ) being determined by least-square error methods, which adjusts the stores as

```
92 SS=SS+XZ * US * US
   US=US-XZ * US * US
```

This movement, however, is subject to the proviso that there is available storage space in the subsoil store which is included in the programme as

```
IF(SS-SSMAX)700,700,701
701 US=US+SS-SSMAX
SS=SSMAX
```

Movement Out of the Subsoil Store

In the original model, movement out of the subsoil store was due to evapotranspiration and flow to ground water, this latter being calculated as a fixed fraction of the water in the store; no account is taken of horizontal flow out of the soil as interflow. This is suitable for small catchments, but the larger the catchment, the greater is the contribution to runoff of interflow and ground-water flow. Thus a component of interflow was added to runoff on this basis of the squared relationship explained above. In calculating the total runoff it is necessary to ensure that the shape, as well as the volume, of the calculated hydrograph matches the actual records, and the movements now described were developed pragmatically to do this.

It is evident from Fig. 1 that once water reaches the open stream channels, the time taken to reach the gauging station would be of the order of a day, or less. Inspection of the raw data showed that hydrograph peaks occurred between two and four days after each rainstorm, hence there is a time of travel through the soil of between about one and four days. This time of travel is accommodated in the model by the use of delay mechanisms depicted by the dummy variables QQ, RR, ST and TT. This is a variation from most models, which account for this delay by using a further store, usually called 'channel storage', but the system used seems to conform more with what actually happens in the catchment.

A further complication occurs when more than 1.5 inches of rain falls in a day. In this case the interception, drainage, upper soil, and subsoil stores would probably be fully satisfied, leaving an excess which would be allocated to surface runoff — thus giving a hydrograph peak on the same day, which does not accord with the facts. The surplus over 1.5 inches (FALL) (X) is therefore dealt with in a similar way to the rest of the rainfall. Surface runoff is first calculated in the normal way, and added to the original surface runoff

```
RUN=RUN+X-F*TANH(A),
```

while the remainder goes into the subsoil store

```
SS=SS+F*TANH(A).
```

This could result in overfilling of the subsoil store, which is tested

```
123 IF (SSMAX-SS) 140,141,141
```

and the excess is called Y

```
140 Y=SS - SSMAX
```

With this condition, the subsoil store contains more than the originally specified maximum, and can be thought of as being 'supersaturated'. Presumably this would provide the conditions for rapid slipping and slumping on steep ground, but this was not investigated.

This excess Y is divided into two, 70% goes into ground water and 30% goes into interflow, these figures being chosen entirely by trial and error. Both parts of Y are, however, subject to the delay mechanism, which works as follows.

The interflow is equated to the dummy variable QQ

```
GRUN=QQ
```

which consists of three parts,

```
141 QQ=QQ+0.005 * SS * SS+0.1 * Y
```

The QQ on the right-hand side is really the previous day's RR, since

```
QQ=RR,
```

this substitution being made after the interflow is equated to QQ.

The second term (0.005 * SS * SS) is the component discussed previously, and the third (0.01 * Y) is that due to the precipitation in excess of 1.5 inches, when this occurs.

RR is itself made up of three similar terms, but based on the previous day's conditions, one of these terms RR, which is equated to ST, being calculated on the conditions two days previous, and so on. In physical terms the quantity QQ can be considered to be the water in the soil near the streams, which will flow into the streams the same day; RR is that further from the streams which moves first into the space occupied by QQ

```
QQ=RR,
```

and then into the streams.

The movement into ground water from the excess Y is similar

```
GW=GW+Q,
```

but in this case Q is only made up to two terms

Q=Q+0.1 * Y,

the Q on the right-hand side being R, since

Q=R.

All the numerical factors in these operations are chosen by trial and error, minimizing the sums of squared deviations of calculated daily runoff from actual daily runoff in the normal manner of steepest ascent.

As in the original model there is also a continuous flow to ground water, the subsoil being depleted by a constant daily factor SS=SS * AAC.

The Ground-Water Store

The ground-water store is an addition to Boughton's model, made necessary by the consideration of the Upper Taieri as a 'large' catchment. Its purpose is to provide a reservoir and a regulator for the ground-water component of runoff.

Water flows into the store from the heavy storms, as explained,

GW=GW+Q   Q=Q+0.1 * Y

and from the subsoil store,

143 GW=GW+SS * (1.0−AAC)

Water is lost from the store by a ground-water component of runoff, provided there is more than a minimum in the store, tested by

IF (GW−BBC) 170,170,171

This minimum value BBC corresponds in physical terms to the condition when the level of the water table is below the bottom of the stream beds, there being then no flow of water into the stream channels from ground water.

As the level of ground water rises, so there will be a small contribution to flow by capillary action into dry stream beds, then an increasing contribution owing to the hydraulic head. The contribution will not be linearly dependent on the water-table level; there will be an increasing ratio of flow to table level owing to (a) the increasing length of stream affected, (b) the increasing height of stream bank available for discharge from the ground-water store and (c) the increasing hydraulic head. Thus a squared relationship was chosen,

171 GRUN=GRUN+ABC * (GW−BBC) * (GW−BBC)

The GRUN on the right-hand side is the interflow component, the second term being the ground-water component, with ABC as a factor chosen by the usual methods.

As in the original model, statement 172 places an upper limit to the ground-water flow. An upper limit of GWMAX was also placed on the capacity of the ground-water store, but in practice neither of these restrictions was brought into effect.

RESULTS

Data Availability

It is evident from the above discussion that the quality of data available is not good. Reliance on a single rain gauge in an area of wide precipitation variation introduces random errors which no minimizing technique can eliminate entirely.

The flow records, to which the calculated values are compared in assessing their accuracy, are themselves subject to error, since they were taken as staff gauge readings once daily at 9 a.m. During storm periods these readings would not necessarily be representative, although during dry spells the fluctuation of stream flow is small.

It cannot be expected therefore that the results can be as good as those obtained under optimum conditions, and hence the object of the experiment is to assess whether results obtained are sufficiently accurate to make the application of digital simulation models a worthwhile operation in these circumstances. It is considered that it would be worth using this model if it gives results which are comparable to or more accurate than other methods which are available for predicting runoff.

Errors in the Prediction of Stream Flow

Daily Stream Flow. The total sum of squared differences between predicted and actual daily runoff amounted to 4.6651 in.^{2} over the 10 years of records used, giving a root mean square value of 0.0358 in. compared to a mean flow of 0.045 in. The average error was thus about 80% of the mean, an apparently unconvincing result. However, much of the error was contributed by a very few days, the worst day in 1917 for example contributing 20% of the total sums of squared differences for 1917. Since this day and most of the other large errors occurred in winter time, it is considered that the lack of knowledge concerning snow melt is the major cause for the failure of this model as a predicter of daily runoff.

TABLE 1 — The accuracy of predictions of runoff, using correlation between rainfall and actual runoff, and between computed and actual runoff, on a monthly basis over a 10-year period.

	Rainfall and actual runoff	*Computed and actual runoff*
Annual	0.271	0.638
January	0.929	0.743
February	- 0.449	0.551
March	0.656	0.367
April	0.593	0.880
May	0.642	0.700
June	0.330	0.377
July	0.443	0.599
August	0.684	0.908
September	0.040	0.207
October	- 0.026	0.733
November	0.470	0.501
December	0.588	0.852

There were also occasions when a hydrograph peak occurred in the observed runoff without any rainfall being collected by the single gauge, indicating that the single gauge did not provide an adequate cover of the area.

Monthly Runoff. Since the present study is associated with an investigation into the water resources of the area as a source of irrigation and domestic supply, monthly stream flow is more useful than daily. Since monthly stream flow is obtained by summing the daily flows, it is to be expected that random errors would be smoothed out, and the higher accuracy of the monthly predictions shows that this does in fact happen. Root mean square error is 0.703 in. compared to a monthly mean flow of 1.31 in. The worst monthly prediction, which was in September 1923, gave an error of 3.58 in., this contributing about 10% of the total sums of squares. The actual figures were:

Rainfall	1.11 in.
Predicted runoff	1.13 in.
Actual runoff	4.71 in.

indicating that either the actual mean rainfall was very much higher than shown by one gauge, or that a considerably greater than average amount of snow melt occurred.

Comparison With Other Methods

The simplest method of estimating runoff from rainfall, given some data, is a simple correlation and regression, possibly using every month together but preferably taking the data month by month. Table 1 shows that the value of this method in this area is very limited, only January providing a high correlation coefficient. If the model is used to predict runoff, then the correlation is increased for all months except two, thus indicating that the model is rather more useful than the simple methods.

CONCLUSIONS

Since for many practical purposes it is not possible to have data which are ideal for use with mathematical catchment models, it is a useful exercise to determine whether the type of data commonly available to engineers and designers can be usefully employed in a model. This exercise has shown that even when the data are far from ideal, it has been worthwhile to develop and use a mathematical catchment model for the prediction of runoff, although it must be admitted that the final results fall short of what is desired for water resources assessment purposes.

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APPENDIX 1

Computer program of the modified catchment model (see also Boughton, 1968) written in Fortran IV for the IBM 360 computer at Otago University.

```
      DIMENSION RAIN(31,12),EVAP(12),FEBETC(12),ROF(31,12),C(12)
      READ (1,1)CEPMAX,USMAX,DRMAX,SSMAX
    1 FORMAT (4F5.2)
      READ(1,1) CEP,US,DR,SS
      READ(1,1) ABC,PCUS,GWMAX,GW
      READ(1,1) FO,FC,AAK,AAC
      READ(1,1) XZ,XY,XX,BBC
      READ(1,2)(FEBETC(J),J=1,12)
    2 FORMAT (12A4)
C CEPMAX IS MAX INTERCEPTION STORE. USMAX IS MAX UPPER SOIL STORE.
C DRMAX IS MAX DRAINAGE STORE. SSMAX IS MAX SUBSOIL STORE.
C H IS MAX LIMIT FOR EVAPOTRANSPIRATION RATE.
C PCUS IS PERCENT ET LOST FROM US STORE.
C FO DAILY INFILTRATION AT ZERO SOIL MOISTURE.
C FC IS MAX INF. RATE. AAK IS K IN INF. EQN. AAC IS FACTOR FOR DEPLETING
C SUBSOIL MOISTURE BY DRAINAGE.
      WRITE(3,500)CEPMAX,USMAX,DRMAX,SSMAX
      WRITE(3,500)CEP,US,DR,SS
      WRITE(3,500)ABC,PCUS,GWMAX,GW
      WRITE(3,500)FO,FC,AAK,AAC
      WRITE(3,500)XZ,XY,XX
  500 FORMAT(4F10.3)
      WRITE(3,3)
    3 FORMAT(12X,'DAY MONTH YEAR   EST   EXCESS  SUBSL  CEP   US
     1DRAIN  SUBSL  SPILL  DEF  GRNDWTR')
      WRITE(3,4)
    4 FORMAT(29X,'RUNOFF  RAIN  STORE  STORE  STORE  STORE')
      F = FO
      CEPMAX = 0
      Q = 0.0
      R = 0.0
      S = 0.0
      DIFF = 0.0
      QQ = 0.0
      H = XX
      DDIFF = 0.0
      RR = 0.0
      ST = 0.0
  223 SPILL = 0.
      SUM = CEPMAX + USMAX + DRMAX
      DEF = 0.
      READ(1,1002)NM,NYEARS,INIT
 1002 FORMAT(3I5)
      READ(1,1003)(C(J),J=1,12)
 1003 FORMAT(12F5.2)
      WRITE(3,1003)(C(J),J=1,12)
      GRUN = 0.01
    5 READ(1,1008)(EVAP(J),J=1,12)
 1008 FORMAT(5X,12F4.2)
      DO 577 J=1,12
  577 EVAP(J) = EVAP(J)/25.0
      WRITE(3,1003)(EVAP(J),J=1,12)
      DO 400 J=1,12
      READ(1,1004)(RAIN(K,J),K=1,31)
 1004 FORMAT(10X,16F4.2/10X,15F4.2)
      DO 401 K=1,31
  401 RAIN(K,J) = 1.08*RAIN(K,J)
  400 CONTINUE
      READ(1,555)((ROF(K,J),K=1,31),J=1,12)
  555 FORMAT(12F6.2,8X)
      DO 102 M=NM,12
      USMAX = USMAX*C(M)
      ROFF = 0.0
      DEFMAX = 0.
      P = 0.
      ROM = 0.
      DIFF = 0.
      DO 101 J=1,31
      Y = 0.
      RUN = 0.0
      EX = 0.0
      DIF = 0.
```

```
      FALL = 0.0
      IF (RAIN(J,M))101,228,125
C THIS DIVIDES DAILY RAIN INTO 1.5INCH LOTS
  125 IF (RAIN(J,M) - 1.5)12,12,126
  126 FALL = RAIN(J,M) - 1.5
      RAIN(J,M) = 1.5
   12 AA = CEP
      AB = US
      AC = DR
      AD = SS
C ADD RAIN TO VARIOUS STORES TILL USED UP
      CEP = CEP + RAIN(J,M)
      IF(CEPMAX-CEP)13,228,228
   13 EX = CEP - CEPMAX
      CEP = CEPMAX
      US = US + EX
      IF(USMAX-US)14,228,228
   14 EX = US - USMAX
      US = USMAX
      DR = DR + EX
      IF(DRMAX-DR)15,228,228
   15 EX = DR - DRMAX
      CALL RATE(F,FO,FC,SS,SSMAX,AAK)
      A = EX/F
      RUN = EX - F*TANH(A)
      DR = DR - RUN
      SSING = F
      IF(SSMAX-SS-F)226,226,229
  226 SPILL = SS + F - SSMAX
      GO TO 229
  228 EX = 0.0
  229 CONTINUE
      RUN = RUN + GRUN
      ROF(J,M) = ROF(J,M)*0.0167
      ROFF = ROFF + ROF(J,M)
      GRUN = 0.0
      WRITE(3,2003)J,FEBETC(M),INIT,RUN,EX,SS,CEP,US,DR,SSING,SPILL,DEF,
     1GW,RAIN(J,M),ROF(J,M)
 2003 FORMAT(16X,I3,A4,I5,12F7.3)
C THIS WRITES OUT VALUES UNDER OLD SYSTEM
      DIF = RUN - ROF(J,M)
      DIF = DIF*DIF
      DIFF = DIFF + DIF
      SPILL = 0.
      DEF = 0.
   11 CEP = CEP - EVAP(M)
      IF(CEP)16,117,117
   16 EP = ABS(CEP)
      CEP = 0.
      US = US - PCUS*FUNCT(US,USMAX,H,EP)/100.
      SS = SS - (100.-PCUS)*FUNCT(SS,SSMAX,H,EP)/100.
  117 IF(DR)18,92,19
   18 DR = 0.
      GO TO 92
   19 CALL RATE(F,FO,FC,SS,SSMAX,AAK)
      IF(DR-F)121,121,122
  121 SS = SS + DR
      DR = 0.
      GO TO 123
  122 SS = SS + F
      DR = DR - F
C THIS USES UP RAIN OVER 1.50. FALL IS RAIN OVER 1.50.
   92 SS = SS + XZ*US*US
      US = US - XZ*US*US
      IF(SS-SSMAX)700,700,701
  701 US = US + SS - SSMAX
      SS = SSMAX
  700 CONTINUE
      IF(FALL)123,123,130
  130 RAIN(J,M) = RAIN(J,M) + FALL
      IF(FALL-1.00)131,132,132
  131 X = FALL
      GO TO 133
  132 X = 1.0
  133 FALL = FALL - X
      A = X/F
      RUN = RUN + X - F*TANH(A)
      SS = SS + F*TANH(A)
      WRITE(3,134)RUN
  134 FORMAT(24X,F7.3)
```

```
       IF(FALL)123,123,130
   123 IF(SSMAX-SS)140,141,141
   140 Y = SS - SSMAX
       SS = SSMAX
   141 QQ = QQ + 0.005*SS*SS + 0.1*Y
       RR = RR + 0.005*SS*SS + 0.1*Y
       ST = ST + 0.03*SS*SS + 0.05*Y
       TT = 0.05*Y
       GRUN = QQ
       QQ = RR
       RR = ST
       ST = TT
       TT = 0.0
       Q = Q + 0.1*Y
       R = R + 0.3*Y
       S = S + 0.3*Y
       GW = GW + Q
       Q = R
       R = S
       S = 0.0
       SS = SS - 0.04*SS*SS
       IF(GW-BBC)170,170,171
   170 GO TO 172
   171 GRUN = GRUN + ABC*(GW-BBC)*(GW-BBC)
       GW = GW - ABC*(GW-BBC)*(GW-BBC)
   172 IF(GRUN-31.3)143,142,142
   142 GW = GW + GRUN - 31.3
       GRUN = 31.3
   143 GW = GW + SS*(1.-AAC)
       SS = SS*AAC
       IF(GWMAX-GW)146,147,147
   146 SS = SS + GW - GWMAX
       GW = GWMAX
   147 DEF = SUM - CEP - US - DR
       P = P + RAIN(J,M)
       ROM = ROM + RUN
       IF(DEFMAX-DEF)22,101,101
    22 DEFMAX = DEF
   101 CONTINUE
       WRITE(3,1007)P,ROM,ROFF,GW
  1007 FORMAT(53X,4F7.2)
       WRITE(3,530)DIFF
   530 FORMAT(10X,'SUM OF SQUARED DIFFERENCES IS', F10.4)
       DDIFF = DDIFF + DIFF
       USMAX = USMAX/C(M)
   102 CONTINUE
       WRITE(3,1019)DDIFF
  1019 FORMAT(10X,'TOTAL SS',F10.4)
       NM = 1
       INIT = INIT + 1
       NYEARS = NYEARS - 1
       IF(NYEARS)30,30,5
    33 GO TO 5
    30 CONTINUE
    32 CONTINUE
       END
/*
// EXEC FORTRAN
       FUNCTION FUNCT(SMLEY,SMMAX,H,ET)
       POINT = H*SMLEY/SMMAX
       IF(POINT-ET)1800,1800,1801
  1800 FUNCT = POINT
       RETURN
  1801 FUNCT = ET
       RETURN
       END
/*
// EXEC FORTRAN
       SUBROUTINE RATE(F,FO,FC,SS,SSMAX,AAK)
       IF(SSMAX-SS)301,301,302
   301 F = FC + 0.01
       RETURN
   302 IF(SS)303,303,304
   303 F = FO + 0.01
       RETURN
   304 F = FC + (FO-FC)/EXP(AAK*SS)
       RETURN
       END
 *
   EXEC LNKEDT
```