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RAINFALL-RUNOFF ROUTING IN THE WAIMAKARIRI BASIN, NEW ZEALAND

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ABSTRACT

The non-linear network model, RORB, is used to compute outflow hydrographs from measured storm rainfalls within the large and steep Waimakariri basin. Rainfall is non-uniformly distributed both in space and time and runoff response is rapid and non-linear. Eight storm rainfall and flow data sets recorded at up to nine automatic raingauges and a single outflow station are used to calibrate and test the model. Calibration involves basin subdivision, assignment of hydrographs to sub-areas and derivation of predictive relations for two model parameters, rainfall losses and baseflow. Peak size, hydrograph shape and arrival time at the outflow site are simulated well in the test runs. Application of the calibrated model to calculate a probable maximum flood for specified rainfalls and other conditions yields results consistent with regional flood frequency information. A useful flood forecast for the outflow station is achievable using telemetry and RORB once three or more hyetographs from basin raingauges have peaked. Suggestions are made for improving model performance and the possibility of coupling RORB with a hydraulic model is briefly reviewed.

INTRODUCTION

A major part of the preparation of a floodplain management plan for the Waimakariri River involved estimating the cost of injury to people and damage to floodplain assets arising from floods overflowing or breaching stopbanks and groynes of the structural protection system (NCCB, 1986). Several scenarios were developed for floodplain inundation caused by channel breakouts during the passage of floods ranging in size up to the probable maximum flood or PMF (Hansen, 1987). Complete hydrographs were required for each event to calculate outflows onto the floodplain under prescribed bank failure conditions.

To generate channel hydrographs for floods larger than those previously recorded, a rainfall-runoff routing model was applied to the Waimakariri basin.

The model was calibrated using both records of storm rainfalls and the resultant flood hydrographs measured at a single downstream gauging station. In addition to design use, the model also provided the basis for a flood warning and forecasting facility which may reduce flood damage (Eriksen, 1986).

This paper reports on the adaptation and employment of the routing model within the Waimakariri basin and describes: (1) model selection and properties; (2) calibration, testing and application of the model to predict a hydrograph for the PMF; (3) use of the model in flood forecasting; and (4) developments which would improve model capability, performance and operation. The aim is to provide an informative example of rainfall-runoff routing in a large, steep basin having a rapid and non-linear response to short duration, high-intensity rainfalls which are non-uniformly distributed in time and space.

RAINFALL—RUNOFF ROUTING MODEL

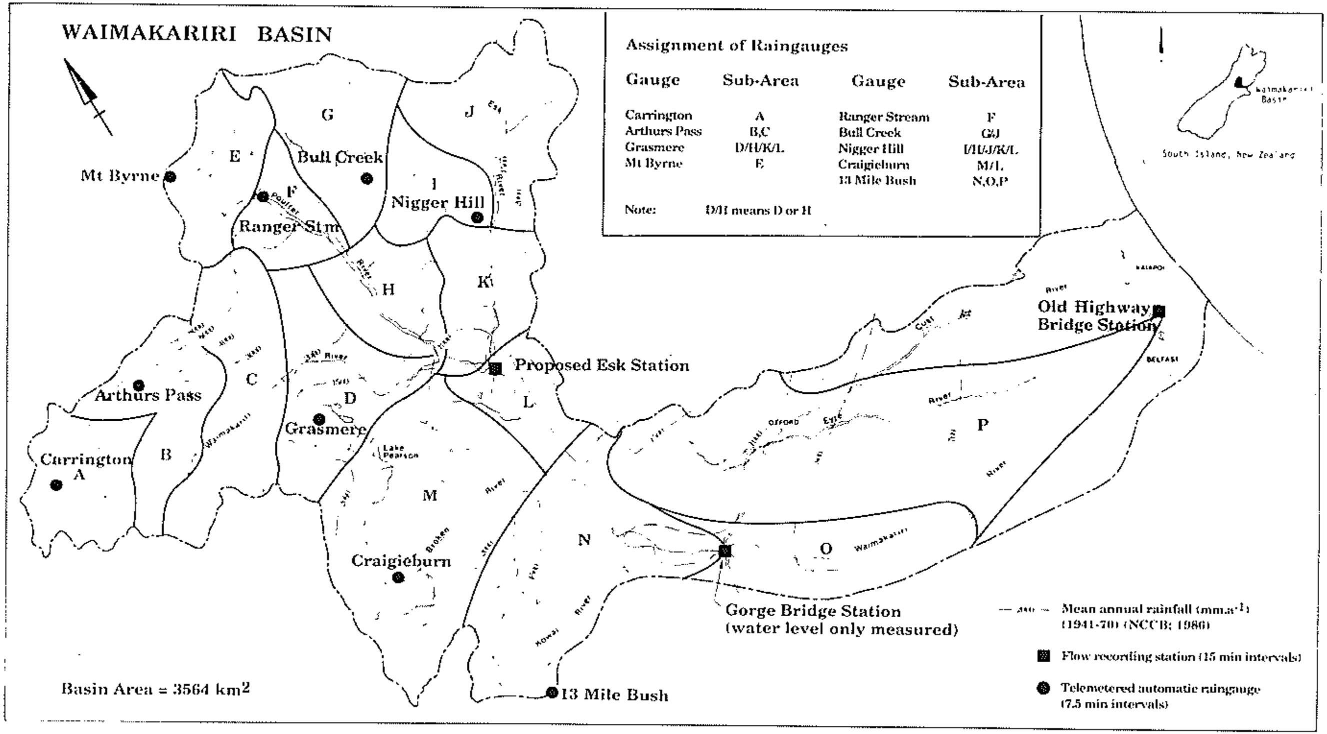
Model Selection

There were four main specifications and relations which a suitable model needed to satisfy. First was the use of available hydrological records. By comparison with many New Zealand rivers, excellent records of rainfalls and flood flows from eight major storms are available for the Waimakariri basin for the period 1957 to 1988. For each storm up to nine different hyetographs were produced by automatic raingauges sited throughout the catchment, and the corresponding outflow hydrograph was measured at the Old Highway Bridge (OHB) flow recording station (Fig. 1). All floods were gauged by current meter at or near the flood peak (Griffiths, 1989a). While some of these records could be used for model calibration the remainder would be needed to test model prediction, from prescribed rainfall, of shape, magnitude of peak and time of arrival of hydrographs at Old Highway Bridge. Second, in calibrating or applying a model present understandings of the pattern of storm rainfalls and the nature of rainfall-runoff relations within the basin should be fully utilised. However, little detailed knowledge is available concerning storm rainfall losses, precluding use of models such as HYCEMOS (NWASCO, 1988) which requires detailed input on this aspect. Third, the relationship between depths of rainfall excess and direct runoff is non-linear within the basin. Fourth, the model must be useful for flood forecasting as well as for design.

Investigation of various types of hydrological models led to the choice of a non-linear network. The RORB model (Laurenson, 1964; Laurenson and Mein, 1985) was selected because it has proved useful elsewhere in New Zealand under broadly similar conditions (A.I. McKerchar, pers. comm.; ARWB, 1989).

Description of Model

RORB is a computer model which routs rainfall-excess through a network of concentrated non-linear storages arranged to represent river topology. Application of the model involves division of a basin into sub-areas and allocation of a temporal rainfall pattern to each one. Gross rainfall is acted on by a loss sub-model to produce rainfall excess, which in turn is converted to a direct runoff hydrograph for each sub-area. This hydrograph is then routed through a non-linear storage representing the effects of overland and subsurface flow and channel reaches. On any branch the hydrograph from the first sub-area



Assignment of Raingauges

Gauge	Sub-Area	Gauge	Sub-Area
Carrington	A	Ranger Stream	F
Arthurs Pass	B,C	Bull Creek	G/J
Grasmere	D/H/K/L	Nigger Hill	I/H/J/K/L
Mt Byrne	E	Craigieburn	M/L
		13 Mile Bush	N,O,P

Note: D/H means D or H

FIG. 1 —Definition of sub-areas, assignment of raingauges, location of hydrological recording stations and distribution of mean annual rainfall in the Waimakariri Basin.

is routed through the first storage: the hydrograph from the second sub-area is then added and so on. At the confluence the final hydrograph is stored until the one from the other branch has been calculated in the same way. The two branch hydrographs are then combined and routed through the next storage. This sequence is repeated until the basin outlet is reached and the complete outflow hydrograph is obtained by adding baseflow (Laurenson and Mein, 1985).

Reach storages are assumed to be governed by a storage-discharge equation of the form

$$S = 3600kQ^m \qquad (1)$$

in which S is storage, Q is outflow discharge and k, m are parameters. The exponent, m, is a measure of basin non-linearity so that $m = 1$ implies a linear catchment. The constant, k, is defined by the product, $k = k_r k_c$ where k_r is the relative delay time of an individual reach storage and k_c is a dimensionless measure of the storage delay time of the whole basin (Malone and Cordery, 1989). Our experience is that m and k_c control both hydrograph shape and time to peak of a hydrograph from, say, the peak of rainfall excess; and that variations in m produce much larger changes than corresponding variations in k_c (see also, ARWB, 1989; p.16).

APPLICATION

RORB may be run in four modes — calibration or fit, test, design, and forecast, although it was initially developed for only the first three modes. For calibration four of the eight storm-rainfall and outflow data sets were selected simply by taking every second event in date order. These were used to derive rules governing rainfall losses, thus defining rainfall excess, and to determine values or relations for the parameters m and k. The other four data sets were employed in testing.

Calibration

Laurenson and Mein (1985) set out the calibration process, which consists of division of a basin into sub-areas; assignment of hyetographs to sub-areas; loss estimation; model parameter fitting; and baseflow addition. The five elements are discussed below:

(1) Basin subdivision

Subdivisions must be fine enough to model basin response adequately. Sub-areas are centered on stream channels or tributaries and are bounded by drainage divides. Other schemes, besides the one shown in Fig. 1 clearly are possible, but our experience indicates that an increase in the number of sub-areas is unlikely to improve performance and, indeed, a reduction in numbers might be considered.

(2) Hyetographs

Fig. 1 details the assignment of hyetographs recorded by the raingauges to various sub-areas. Several options are listed for some sub-areas; and the particular choice for a given storm would depend on its nature and direction of movement. In this way the total amount of storm rainfall and its distribution in time is supplied to each element. If a rain gauge is not centrally located in a sub-area, then the rainfall amount is scaled according to the findings of Whitehouse (1985) by the ratio of the mean annual rainfall for the sub-area (assumed to fall at the centroid) to the mean annual rainfall at the gauge, using the spatial distribution of mean annual rainfall outlined in, Fig. 1. Similarly, for an area without a gauge, the assigned total is scaled by the ratio of the respective mean annual rainfalls for each sub-area. Finally, RORB runs in hourly steps from a selected start time; and the differing hyetographs begin contributing rainfall to sub-areas with the same time lags between them, if any, that occurred in actual storm recordings.

(3) Losses

RORB offers two loss models, the more flexible of which allows specification of an initial loss, L_i, and a constant continuing loss rate, L_r. Our data indicates that losses are strongly dependent on antecedent wetness, because response hydrographs vary with antecedent wetness for similar rainfalls. Experimentation with fit runs involving balancing of rainfall excess with measured direct runoff led to the development of a linear relation between L_i and the 2-day antecedent rainfall index, P_a, at Arthur's Pass rainfall station (Fig. 1) — the chosen index station for the Waimakariri basin. For example, if a storm began on day n then P_a would equal the rainfall on day n-1 plus half that on day n-2. In like manner, L_r was found to be a non-linear function of L_i.

(4) Model Parameters

A procedure given by Weeks (1980) was used to determine optimum values of m and k_c. It was found that m was best left set for all runs at m = 0.8, the value recommended by Laurenson and Mein (1985). This matter is discussed again later. With m fixed, $k = k_r k_c$ remains to be determined. Now, k_r is a prescribed function of stream lengths and is calculated by the programme from data supplied for the basin. Thus k_c is left to be determined from storm rainfall and outflow data and, as noted above, it controls lag time. Extensive trials involving both calibration and test runs resulted in a relation between k_c and the time to peak of the hyetograph at the index rainfall station at Arthur's Pass (Fig. 2). For a hyetograph consisting of more than one burst of rain, the time is taken from

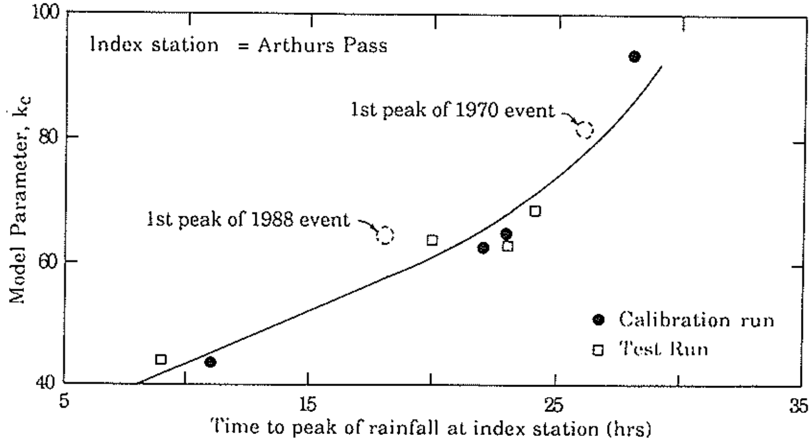


FIG. 2—Relation between RORB parameter, k_c, and time to peak of rainfall at Arthur's Pass index rainfall station.

the last burst to occur. This relation is a successful predictor, probably because the time to peak of the index rainfall is highly correlated with the time difference between peak of rainfall and peak of outflow hydrograph; and k_c is a function of this lag time.

(5) Baseflow

Compared with peak flood discharges, baseflows are very small quantities, but cannot be ignored when a complete flood hydrograph is sought. For prediction, a linear relationship was found between baseflow and time of rise of the outflow hydrograph. Because baseflow is appended to the direct runoff hydrograph after a RORB run in any mode, time of rise is obtainable from run output.

Testing

The four storm-rainfall and outflow data sets not used in calibration were used to test model performance as a whole, as well as the predictive relations for L_i, L_r, k_c and baseflow. The results (Table 1) are very good given the complexity of the phenomenon being modelled and the stochastic nature of some of the processes involved. At OHB the estimated standard error for peak difference is ± 14% and for peak arrival time, ± 0.83 hours. Details of a typical measured hyetograph at Arthur's Pass rain gauge and the related measured and predicted hydrographs at OHB are shown in Fig. 3. The shape of the body of the hydrograph is also adequately modelled. Different selections of calibration and test examples chosen at random (following O'Donnell et al., 1988), give slightly better or worse test performances. Sensitivity analysis indicates that some combinations can produce peak size differences up to ± 25% and timing differences up to ± 2.5 hours. This behaviour stems from the limitations of a small data set in predicting loss, parameter and baseflow values. As more data sets become available accuracy will improve: for example, use of any six sets for calibration yields maximum

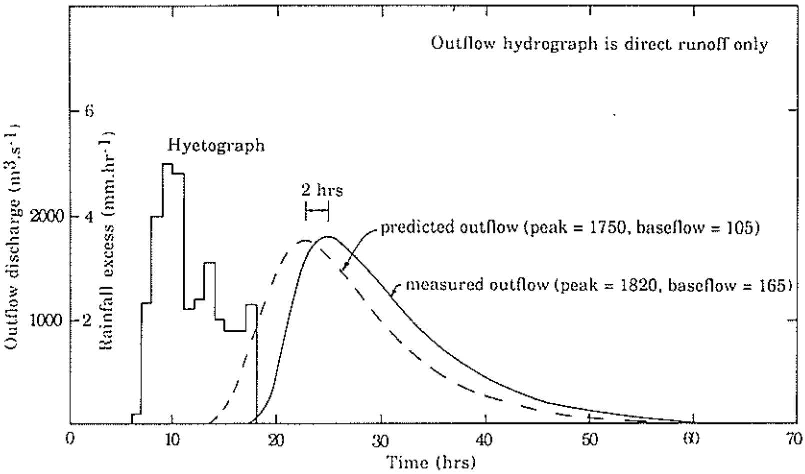


FIG. 3—RORB model fitted to the May 1988 flood event (Table 1). Single hyetograph shown is for the index rainfall station at Arthur's Pass.

TABLE I—Calibration and test results for RORB modelling of large floods in the Waimakariri Basin (1957–1988)

Run Type C = calibration T = test	Date of Flood	Peak Flow at OHB ($m^3.s^{-1}$)	Return Period of flood (yrs)	Return Period of rain at Arthur's Pass (yrs)	Initial Loss L_i (mm)	Continuing Loss L_r ($mm.hr^{-1}$)	k_c	Peak Size Difference at OHB (%)	Peak Arrival Time Difference at OHB (hrs)
C	11.03.67	2050	6	3	38	4.18	63	-1.1	0
C	02.04.75	1170	4	5	59	3.85	42	+0.8	0
C	24.11.84	2830[2]	-	-	60	1.70	65	+0.7	0
C	13.09.88	2298	9	4	20	2.40	94	+7.1	-2
T	27.12.57	3990	100	90	42	4.25	61	-4.1	2
T	31.08.70	2710[1]	-	-	37	4.30	71	-20.0	0
T	03.12.79	3020	24	30	39	4.40	68	+20.0	1
T	20.05.88	1985	6	7	39	4.40	44	-6.6	2

Note: (i) m = 0.8 for all runs
(ii) a positive difference in peak size implies over-estimation
(iii) a positive difference in arrival time implies predicted peak is early
1 double peak flood, data for second and largest peak to arrive
2 triple peak flood, data for third and largest peak to arrive

peak errors of about ± 10% and timing errors of ± 1 hr. In terms of the information requirements for management of flood emergencies, however, the overall performance is entirely adequate.

A further point of interest concerning the hyetographs at Arthur's Pass and the OHB hydrographs is their return periods for a given storm (Table 1). Rainfall return periods were determined from an analysis of Arthur's Pass records and from Tomlinson (1980), taking duration for each storm as the time of rise of the hydrograph at OHB. This is, perhaps, a measure of the time of concentration or equilibrium of the basin, which appears to depend on rainfall intensity (Henderson, 1966, p. 397). Peak outflow return periods were calculated from flood frequency analyses of annual maximum series at OHB reported by Pearson (1988) and Griffiths (1989a, 1989b). Agreement between rainfall and flow results is well within estimated standard errors. It is poorer for small storms where variations in rainfall pattern and losses can be significant.

Design

The most interesting and difficult design problem was estimation of the PMF at OHB outflow station under present climatic and physical conditions in the basin. Frequency analyses of rainfall records for Arthur's Pass indicated that, of the two relations given in Tomlinson (1980, Fig. 6) for probable maximum precipitation (PMP) as a function of rainfall duration, the one which predicts lower values and is based on the highest rainfall intensities in New Zealand matched the records better, although still predicting slightly higher values (i.e. conservative). WMO (1986) precipitation maximisation techniques were also attempted with Arthur's Pass rainfalls but there is insufficient meteorological data available to derive sound results.

In running RORB to calculate a design PMF, the 24-hr PMP value determined in this manner and adjusted by an area reduction factor (Tomlinson, 1980, Fig. 7) was assumed to fall on sub-areas A and E (Fig. 1), the wettest in the basin. Total rainfalls on other segments were distributed in proportion to the distribution of mean annual rainfall, relative to A or E (which have the same annual values). Hyetograph shape for a particular duration was selected from corresponding recorded cases, which for any given duration are very similar. All rainfall was deposited simultaneously on the sub-areas. Initial and continuing losses were set at median values in view of the conservatism of the rainfall inputs, and k_c was determined from Fig. 2. Results of these PMF calculations for various durations are listed in Table 2. The maximum discharge of some 8000 m^3 s^{-1} occurs for a 24-hour duration rainfall and has an estimated standard error of approximately ± 1000 m^3 s^{-1}. This value may be accepted as the design figure.

It is common practice in Australia and elsewhere to take the PMF peak as the 10^5 year flood (Rowbottom et al., 1986). From at-site and regional flood frequency analyses performed by Pearson (1988, Figs. 1, 2 and 3), Griffiths (1989b, Fig. 4) and McKerchar and Pearson (1989) the 0.001% annual exceedance probability flood is 7000 ± 1000 m^3 s^{-1}, in agreement with the RORB calculation to within a standard error. A PMF of around 8000 m^3 s^{-1} or five times mean annual flood may seem high; but Costa (1987) lists recorded floods exceeding 10,000 m^3 s^{-1} in basins with nearly the same contributing areas and a similar maritime climate.

TABLE 2—Estimates of probable maximum flood peak magnitudes for given rainfall durations — Waimakariri River at Old Highway Bridge

Rainfall Duration at Arthur's Pass (hr)	Probable Maximum precipitation depth at Arthur's Pass (mm)	Initial loss, L_i (mm)	Continuing loss, L_r ($mm.hr^{-1}$)	k_c	Lag time = peak of rain to peak of outflow (hr)	Flood Peak at OHB ($m^3.s^{-1}$)
12	445	60	3.10	35	10	5660
18	555	60	3.10	40	10	6535
24	650	60	3.10	44	10	7615
30	735	60	3.10	58	13	5410

Forecasting

In this mode RORB is used to predict an outflow hydrograph at OHB given telemetered rainfall information from the upper basin (Fig. 1) and appropriate values for losses, k_c and baseflow defined by relations determined in the calibration process. As in all previous runs the model parameter m is set to m = 0.8. An early forecast is achievable once hyetographs from at least three of the upper basin gauges, including Arthur's Pass, have reached their peaks. Storm records show that all raingauges start measuring rainfall within two or three hours of each other but cease at widely differing times. This early information allows prediction of peak magnitude and timing of the OHB hydrograph with a standard error of ± 16% for size and ±1 hours for time of arrival. Lead time between prediction of peak and peak arrival averages 15 hours. Subsequent model runs executed as a storm progresses, and more rainfall data becomes available, improve slightly in accuracy until, when a storm is over, the results of Table 1 (test runs) are obtainable.

The effect of increasing information and repeated runs is largely to fill out or expand the falling limb of the outflow hydrograph: the shape of the rising limb, its peak and timing are dominated by the nature of the same features of the hyetographs in the upper basin.

Operation of RORB as a forecasting tool is a straightforward but detailed process requiring care. Accordingly a written procedure has been produced to optimise model running and to ensure that results for a given storm are repeatable.

FUTURE WORK

As additional data on rainfall and flows becomes available from large storms, rainfall-runoff routing models more sophisticated than the non-linear network type could be applied to the basin. Meanwhile the performance of RORB could be improved in several ways: (1) different RORB models could be fitted to major sub-catchments, with a better partitioning into sub-areas; (2) further studies on storm behaviour, hyetograph properties and intensity-frequency-duration relations would improve prediction of extreme rainfalls and hyetograph shapes; (3) the relationship between model parameters m and k_c requires more detailed investigation for, if k_c is variable, then so probably is m; and (4) loss rates are known to depend on season, and the extent and temperature of snow cover, so these influences need to be accommodated in predictive relations for initial and continuing loss.

Goring (1988) has shown that, between Gorge Bridge flow station (Fig. 1) and OHB, floods can be routed very accurately using kinematic waves. The routing method was calibrated using stage or water level hydrographs of floods at the Gorge (the site is too turbulent for gauging at high flow) together with the corresponding stage and flow hydrographs at OHB. One outcome of this finding is a proposal to install another stage-only station at Esk (Fig. 1) — again turbulent but the only practical site, and to attempt similar hydraulic routing between this station and OHB. The effect of tributary inflows between the two sites is minor in large storms. If successful it will provide a useful, independent check on RORB predictions for OHB, once a flood wave passes Esk; and if it proves more accurate then use of RORB could be mainly confined to predicting hydrographs at Esk.

CONCLUSIONS

The principal conclusions of this study are:

(1) The non-linear network model RORB is suitable for rainfall-runoff routing in the Waimakariri basin given the type of rainfall and flow records available; a non-uniform distribution of rainfall in space and time; non-linear basin response; little information about loss rates; and the need to employ the model for flood forecasting.

(2) Model performance in predicting peak size, arrival time and the shape of four of eight measured basin outflow hydrographs given measured storm-rainfall inputs is very good, provided the other data sets are used to calibrate RORB with respect to model parameters, rainfall losses and baseflow for a prescribed basin subdivision and assignment of hyetographs in sub-areas.

(3) Application of the calibrated model to calculate the PMF at the outflow station, under present climatic and physical conditions and for specified PMP values gives results consistent with regional flood frequency information.

(4) A useful forecast of the outflow hydrograph is achievable using telemetry and RORB once three or more storm hyetographs from the nine upper basin raingauges have peaked.

(5) Improvements in model performance are likely with further study of basin hydrology and collection of more data for calibration particularly as regards rainfall losses. There is a prospect that a hydraulic routing model can be coupled with RORB and replace its use in the lower basin.

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