Application of GIS in Analysing Spatial Patterns of Multiple Runoff Events

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Abstract

Rainfall, topography and soil characteristics are considered to control spatial redistribution of phosphorus in catchments. To advance this research, a hydrology model is needed to describe spatial variation of soil moisture dynamics and runoff source areas in multiple runoff events. This study examined whether the spatially distributed, topographically based rainfall-runoff model, TOPMODEL provides superior performance for rainfall/runoff events in maritime climate and pastoral hill lands like New Zealand. Unlike previous efforts, we evaluate the hydrological model to identify runoff source areas for each individual runoff event. Geographical information system was used to analyse the model sensitivity on pattern dynamics of runoff, water tables and soil moistures of three major runoff events (low, medium and high). The model was tested for two catchments at Waipawa in Palmerston north, New Zealand. The study confirmed that TOPMODEL give high quality results (R^2 of 84%) when validated against flow observations. Visual analysis on GIS systems showed that the predicted dynamics of variable source area and the component hydrological processes is realistic in the study area of pastoral farmlands. The TOPMODEL can be used to reflect both long-term evolutionary soil moisture content patterns and the short term forcing of flow dynamics during storm events in typical New Zealand mountainous and high rainfall volume (1200mm/year) regions.

I. INTRODUCTION

The modern geographical information technologies have facilitated recent progresses in hydrological modelling with precision digital terrain models and soil physical properties (Schumann et al., 2000). Rainfall, topography and soil characteristics are considered to control the spatial redistribution of phosphorus in catchments (Beaujouan et al., 2001). To model this process, a rainfall-runoff model is required to provide realistic estimates of runoff and associated contributing areas in multiple rainfall events.

TOPMODEL is a physically based rainfall-runoff model (Beven and Kirkby, 1979) that is able to predict stream-flow, and to potentially quantify those areas of a stream basin most likely to generate overland and subsurface flow (Beven et al, 1984; Connell, 2001). It also can be used to estimate the depth to the water table in a catchment. The model has been well tested for the climate and land physical conditions in European countries (Donnelly-Makowecki and Moore, 1999; Perrin et al., 2001; Quinn et al., 1998). In New Zealand maritime climate, weather is highly changeable, and average annual rainfall volumes are excessive (1200mm). The majority of New Zealand farmlands has complex of undulating terrain covered by animal grazing pasture, and has diverse soil physical properties. Although there have been several experiences of using TOPMODEL in south hemispheric climatic regions, they mostly aimed at predicting flood disasters, and hydrologic loading quantities at meso-scales (Ibbittt et al., 2000; Bren, 2000).

In this paper, we present a case study to summarize our experience of calibrating the TOPMODEL for the New Zealand farmland conditions and practice of using a non-linear regression package to optimise the prediction of outlet flow hydrographs. The case study was conducted at two small catchments (12.8 and 12.6 hectares) at Waipawa in Palmerston North, New Zealand. The two catchments were animal grazing farmlands and chosen as our fertiliser trial site. The study was then further extended to evaluate the applicability of TOPMODEL for simulating the variation of runoff source-area. Three runoff events of different flow volumes (low, medium and high) were used for the sensitivity test of the model. The patterns of spatial distributed water tables, soil moisture contents, and runoff generations was analysed with GIS approach. Topological and soil physical properties are presented in $20m^2$ grids. Outlet hydrographs and rainfall used in the study was measured between January and July 1999. The data of the first six months were used for the calibration. The model was validated with the July data.

Owing to the difficulty of measuring appropriate data on all aspects of catchment runoff, spatially distributed models like TOPMODEL are often adjusted to only fit outlet flows. This limits the reliability with which some runoff components, e.g. overland flow, can be estimated (Yu et al., 2001). Work in progress at another research site, Whatawhata, in Hamilton, New Zealand is intensively measuring temporally varying hydrological data with a view to improving the reliability with which runoff components can be estimated (Ibbitt, 1996).

1082-4006/00/0701-16$5.00

Successes with the Whatawhata work suggest that even when TOPMODEL is fitted to catchment outflows only, useful information can be gained from the model results about such things as areas of concentrated surface runoff and dynamics of distributed water tables. Instead of waiting for the field data to prove the model reliability, GIS approach was applied to confirm TOPMODEL's capability in estimating pattern dynamics of water table, soil moisture distribution, and runoff source areas for the study site.

II. METHOD AND MATERIALS

Topographical data

The digital elevation model (DEM) of the two catchments of the fertiliser trial site was derived from coverage of contour lines in Figure 1. The contour interval of the map was 5 metres. A small section of the north basin was not included in the original contour line coverage. To fix this problem, we extended the contour lines at the north end by digitising a portion of a 1:50,000 map (NZMS 260 V22). The original (blue lines) and modified (green lines) contour coverage can also be seen in Figure 1. The two basins used for this modelling exercise were delineated from the two weir points specified in the figure. The basins are highlighted in orange colour with darker tones describing higher elevations. Streams (light blue lines) in these two basins were derived from the DEM. Areas of the catchments are 12.8 and 12.6 hectares for the north and south catchments, respectively.

Rainfall, flow and temperature data

Rainfall and flow data were logged in 5 minutes intervals. Rainfall gauges were located 10 metres south of each weir. Flow data were collected at the two weirs. These data cover the period from April 98 to July 99. Because of leakage of the weirs, flow data before November 1998 were unreliable and were not used. At 5 minutes temporal resolution it was not practical to calibrate the model because of the computer resource needed. Consequently hourly mean values were used for both calibration and validation. Mean hourly rainfall and flow for south and north basins are shown in Figure 2a & 2b, respectively. The temperature data were also re-arranged into hourly averages as displayed in Figure 3 to match the time interval used for the rainfall and flow data. A meteorological station at Napier Aerodrome (about 25 kms south of the study site) provided the temperature information. It is the nearest station for which hourly data are available.

Soil type

Waipawa silt loam (shallow phase) is the dominant soil type for the south catchment. Both Matapiro silt loam and Waipawa silt loam are the dominant soils for the north catchment. Previously derived linkages between soil type and soil hydraulic properties provided in the New Zealand Land Resource Inventory (LRI) spatial database were used to estimate appropriate values on soil parameters. Since these parameters are used only during the initial stage and are refined during calibration, their actual value is not critical.

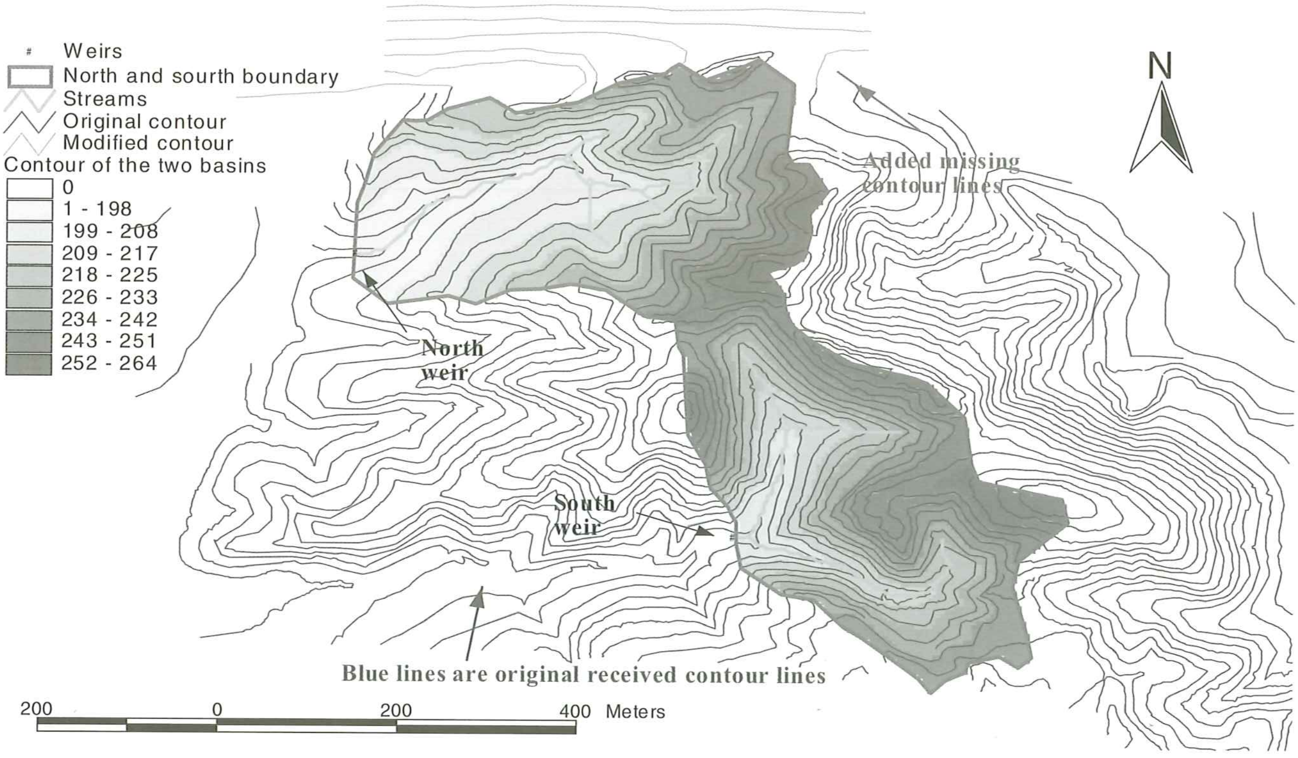


Figure 1. Contour maps at 5 metre intervals for the North and South Waipawa catchments

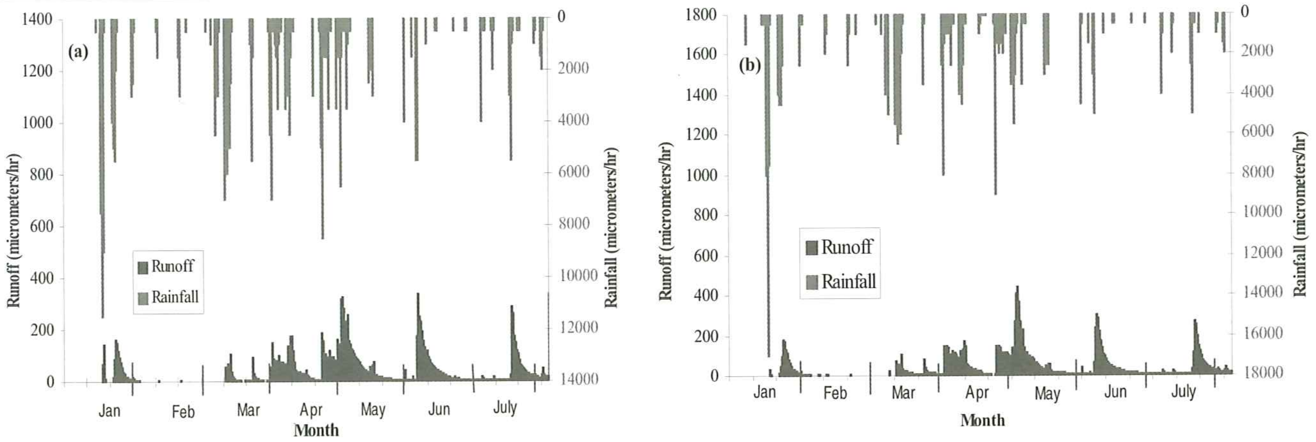


Figure 2. Average hourly rainfall and runoff measured at the Waipawa for the first 7 months of 1999, (a) for the south weir and (b) for north weir

Model description

TOPMODEL includes the following five component processes: (a) surface runoff (infiltration and saturation excess), (b) evapo-transpiration, (c) flux to soil moisture, (d) seepage to water table, (e) lateral seepage from ground water. Surface runoff was generated both when the rainfall rate exceeds the infiltration capacity of the soil and when rain occurs over saturated zones. Flux to soil moisture could be either positive or negative. The positive value is indicative of infiltration and negative represents evapo-transpiration. Surface runoff is routed to stream channels where groundwater flow is added before the combined input is routed down the stream channel. The model description details can be found in Wolock (1993).

III. CALIBRATION

The calibration process matches computed catchment runoff to measured runoff by adjusting the values of 12 key model parameters. Optimal parameter values were estimated with a non-linear regression computer software packages. The calibrated parameters are listed in Table 1.

From Table 1, we can see that the main parameters (f, k, dtheta1, soilc, chv) for the two catchments have similar values. They are intuitively reasonable. For example, the soil moistures between wilting point and saturation for the north and south catchments respectively are 35.6% and 37.2% (dtheta1% + dtheta2%). These values compare favourably with the highest soil moisture levels measured which are about 55% by weight on southern slopes and about 45 % by weight on northern slopes (0-75mm depths) if an allowance of 20% is made for the moisture content below wilting point (Allan Gillingham pers. Comm.).

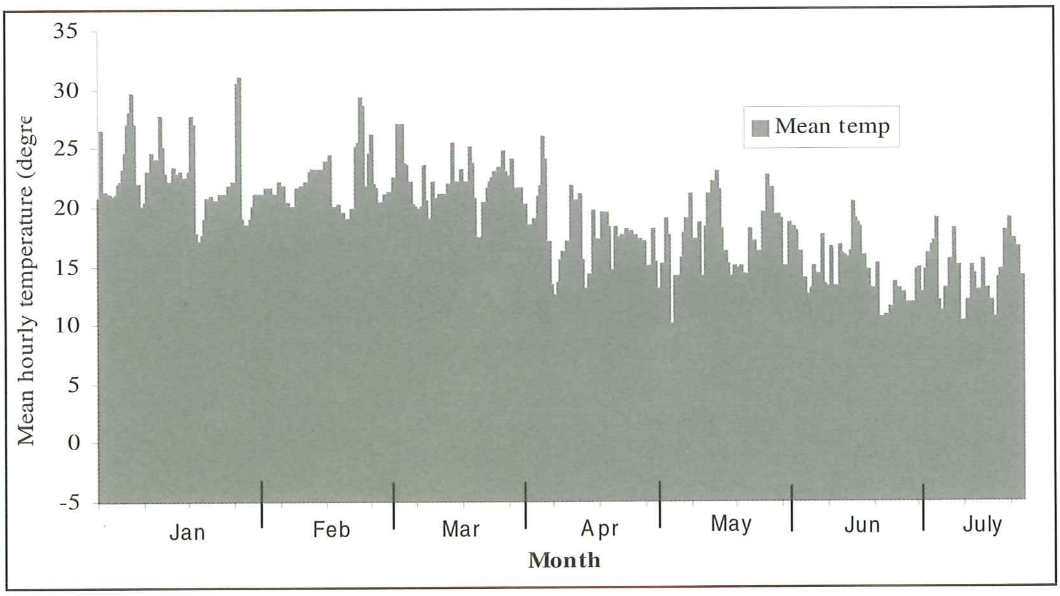


Figure 3. Average hourly temperature measured at Napier station

Table 1. Calibrated TOPMODEL parameters for simulating the Waipawa catchments

Symbol	Description	Unit	Value (North)	Value (South)
f	Control hydraulic conductivity with depth	m^{-1}	5.78	4.8
k	Saturated hydraulic conductivity	m/h	0.01	0.0071
dtheta1	Moisture content between field capacity and saturation	(-)	0.156	0.143
dtheta2	Moisture content between wilting point and field	(-)	0.2	0.229
soilc	Capacity of the unsaturated moisture store	(m)	0.0677	0.05
c	Exponent in the soil moisture - hydraulic conductivity	(-)	0.0942	1.27
psif	Depth of capillary fringe	(m)	0.3	0.3
chv	Velocity of overland flow	(m/h)	1.22	1.3
cc	Canopy capacity	(m)	0.00121	0.00046
cr	Factor for enhancing potential rate of evaporation	(-)	1.45	0.38
albedo	Ratio of out-going to in-coming solar radiation	(-)	0.265	0.155
n'	Mannings roughness coefficient	(m0.333/	0.0065	0.0065

Calibration initially used data at 5-minute intervals for a storm event in June 1999. The model explained more than 98% of the variance in the record. However, validation simulation with earlier data between Jan and May 99 were only partially successful. The main reason for the poor validation simulations compared to the calibration runs was that the short calibration period in June provided the model with little information concerning the drying out of the land following rainfall, particularly in a seasonal context.

Calibration using 6 months data at 5-minute intervals was attempted, but the demands on computer resource were too great and had to be abandoned as impractical. Instead we calibrated models of both catchments using hourly data over a 6-month period.

The results of these calibrations are shown in Figures 4. In the case of Waipawa South 79% of the variance in the record was explained by the model while for Waipawa North this value rose to 84%.

It was noted during the calibration, the Waipawa South catchment received less measured rainfall than the Waipawa North catchment but generates more flow. A physical explanation for this could be that the aspect of North catchment encourages more evaporation, but an equally plausible explanation is that the two rain gauges are differently exposed. Given that rain gauge exposure can underestimate the measurement of rainfall by 5 to 10% depending upon wind conditions, it is not possible to provide a definite explanation for the differences.

IV. MODEL TESTING

Runoff flow

The model's prediction ability for catchment flow was assessed with data for the period between 4200 and 4870 hours from Jan 1 1999 (7th July to 19th July) as shown in Figure 4. The model was able to explain up to 67% of the variance in flows in the catchments. This validation result was derived using calibrated parameter values from the Jan - June period. The model is able to calculate up to 92% of the flow variance, when we adjusted the parameter for the initial depth to the water table. This parameter was adjusted so as to match the simulated flow at the start of the validation period to that measured.

Spatial patterns

The model's ability to predict the spatial patterns of surface runoff generating areas, minimum water table depth, soil water content and cumulative flux (infiltration or evapo-transpiration) could not be directly assessed with field information. In order to provide some idea of the model's potential ability for estimating these items, three flow events from the period used for calibration of catchment flow have been selected for examination in a spatial context. As indicated in Figure 4, the first event was in the period 475 - 890 hours (Jan. to Feb.), the second was for 2690 - 3560 hours (April to May), and the third event was for 3561 - 4200 hours (late May to late June). The total rainfall, measured and predicted runoff are summarised in Table 2.

During the first event generally dry conditions prevailed. The model results for that event therefore indicate what can be expected when the catchment is dry. After the January storm, the catchment drained and dried until April. Towards the end of April the largest event in the calibration period occurred. This event represents the transition from dry to wet conditions. The final event studied was in June during winter, for which antecedent conditions were wet For each event there are 4 plots of spatial patterns. These spatial patterns vary from summer through to winter, and with size of the rainfall. These are explained as follows.

Table 2. Summary of the flow events for the north and south catchments

	Waipawa Nth			Waipawa Sth		
Event No	Rainfall	Measured	Predicted	Rainfall	Measured	Predicted
1	87000	10915	11004	77000	13485	13547
2	122500	59788	59119	121500	64416	65775
3	59000	32318	25819	55000	29863	22970

Surface runoff areas

Figure 5 is the spatial patterns of surface runoff for each event. It consistently shows that valley bottoms and small high ridge areas generated runoff (mostly saturation excess runoff). The extent of runoff-generating areas increases with both event size and time of the year. Most runoff is from areas where the water table has reached the surface of the ground (around stream areas). In the January event surface runoff occurred only from areas close to the channels. In the larger April event, runoff occurred from areas some distance from the channels. Similar patterns were simulated in June, but the smaller size of this event limited the extent of the runoff-generating areas.

Minimum depth to the water table

The minimum depth from the ground surface to the water table for each pixel for each event is shown in Figure 6. Note that these minima need not all occur at the same time across each basin. The plots of minimum water table depths reflect the amount of rainfall that fell in each event. During the April event, water table levels over much of the catchments came close to the surface. The pattern of water table depth for the June event is similar to the April event, indicating that during the April event the water table rose to levels more often associated with winter conditions.

Distribution of initial moisture

The model determines soil water content on the basis of soil type and depth to the water table. The assumption of uniform soil type over both basins mean that in the absence of any other influence the initial soil moisture at all conditions will be the same. Each catchment has been sub-divided into a number of sub-basins (11 for the South catchment and 17 for the North catchment) and differences in the mean position of the water table in each sub-basin leads to sub-basin differences in initial water content. This is an expected result and is visible in Figure 7.

Cumulative flux (infiltration or evapo-transpiration) areas

The cumulative flux can be either infiltration or evapo-transpiration. During rainfall, the flux is infiltration and is positive. Between rainfall events the flux is negative, representing evaporation from the soil as soil moisture is depleted. Wet areas generally have a water table close to the surface and this limits the infiltration because there is simply not enough space in the soil to absorb the incoming rainfall before the soil becomes saturated. In such areas the evapo-transpiration can continue at rates higher than on the hillsides because of the greater availability of moisture arising from the water table being closer to the surface. After rainfall, the wet areas sustain a higher rate of evaporation. Effectively the soil moisture in these locations is supplemented by drainage from up-slope locations.

Figure 8 shows the cumulative flux to the soil for the three events, respectively. The extent of wet conditions mainly reflects seasonal variations and the size of storm rainfalls. There are more high infiltration areas in event 1 than the other two, because of the dry conditions before the event. It is also the event of smallest duration. Results for event 2, which has the largest rainfall, showed an increase in areas of high evapo-transpiration rates. These mostly occurred around wet stream channels. The results also show less infiltration on the higher ground. Event 3 occurred in the winter and has the wettest pre-event conditions. Its evapo-transpiration intensity is the least of the three events. Event 3 was of intermediate duration, and its infiltration and evapo-transpiration areas are in between those for the other two events.

Topographic index values (A/tanB)

TOPMODEL simulates the effect of topography by constructing an index for each pixel in the landscape. This index is a combination of the upstream area, A, draining through each pixel and the slope of the ground, tan(B), at the

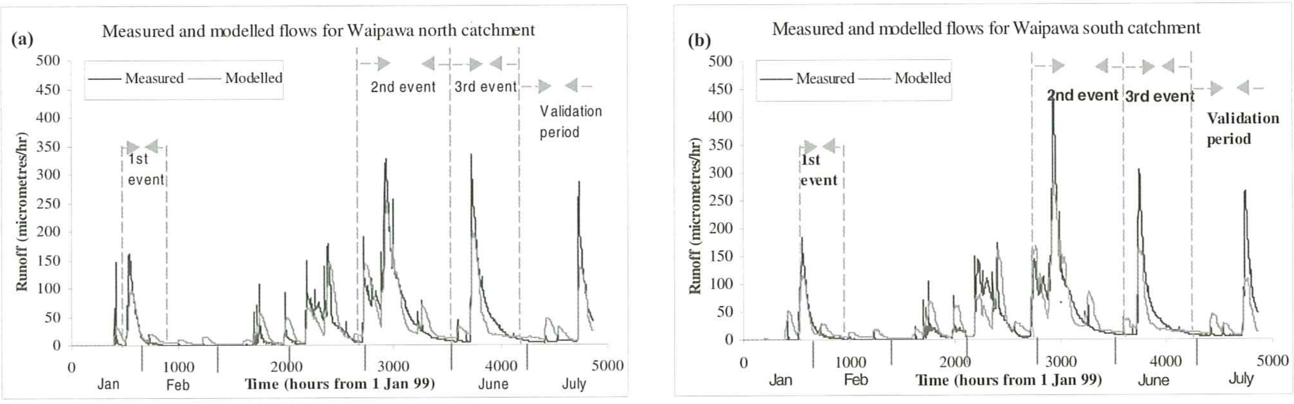


Figure 4. Measured and modelled flow rate for Waipawa (a) for North catchment, (b) for South catchment

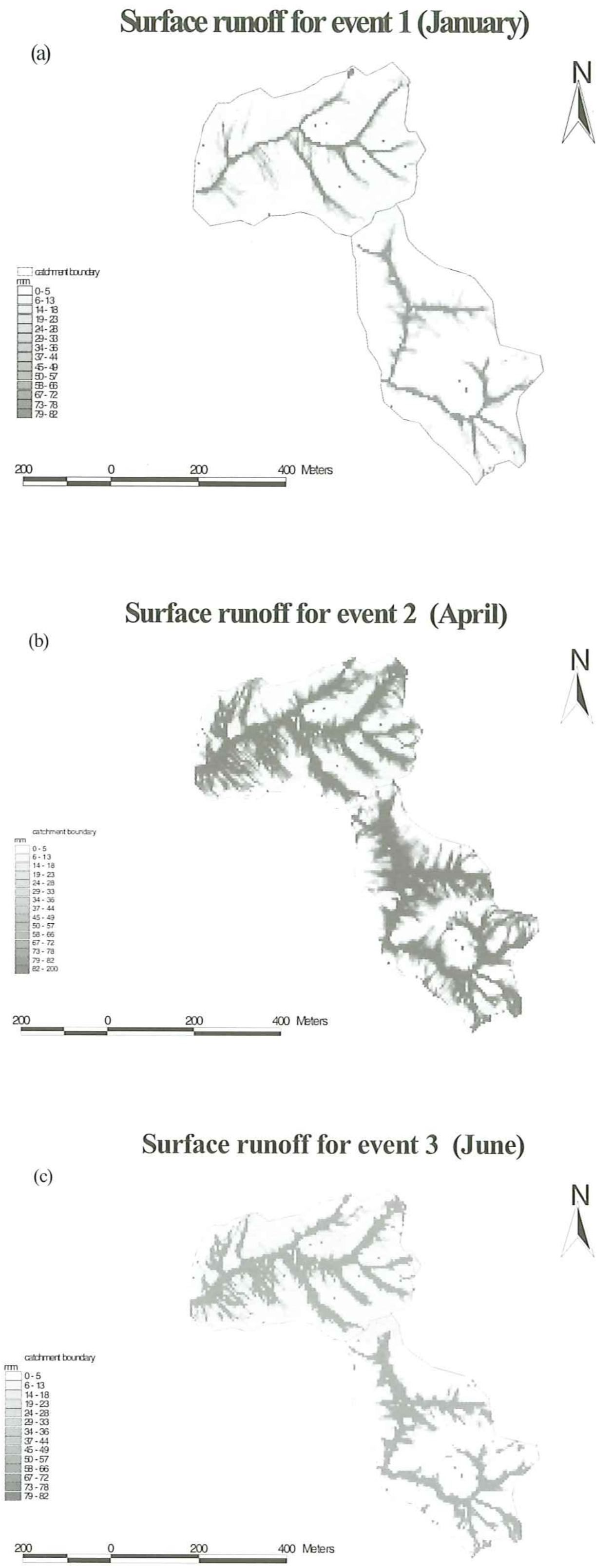


Figure 5. Spatial patterns of runoff contributing areas from the three flow events (mm in depth during the event), (a) low runoff, (b) high runoff, and (c) for medium runoff.

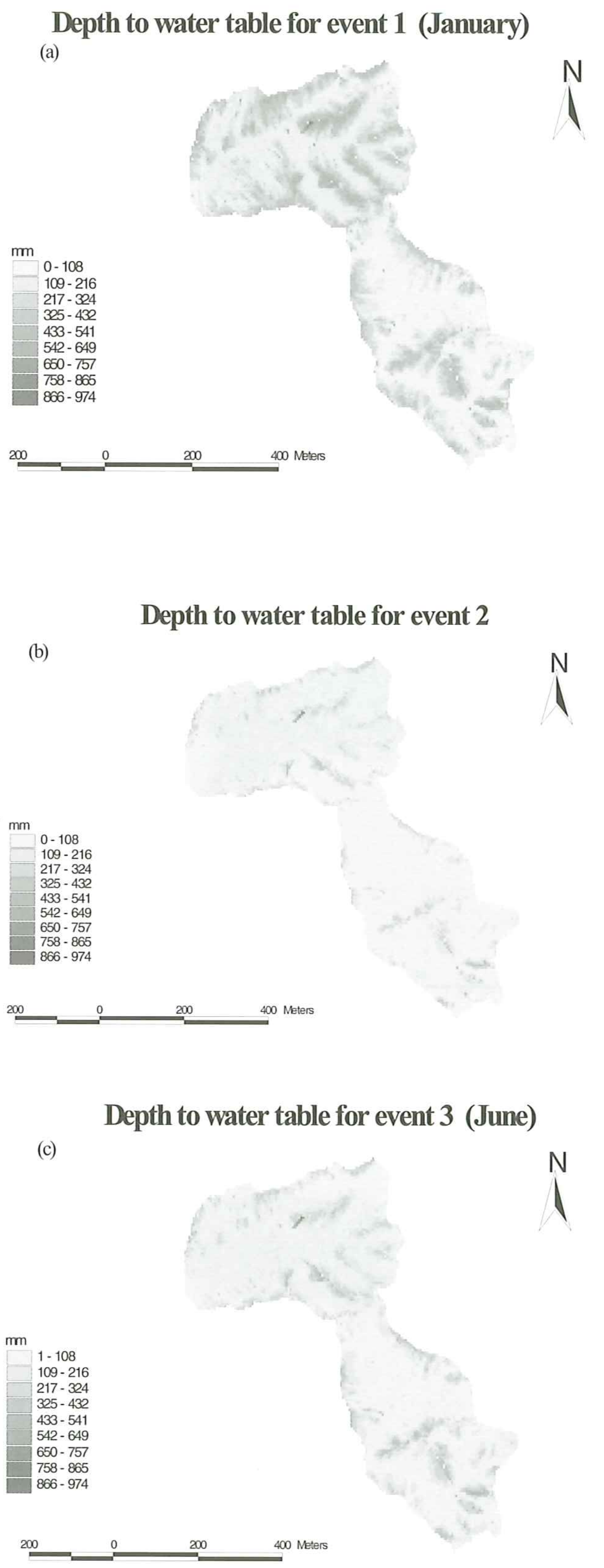
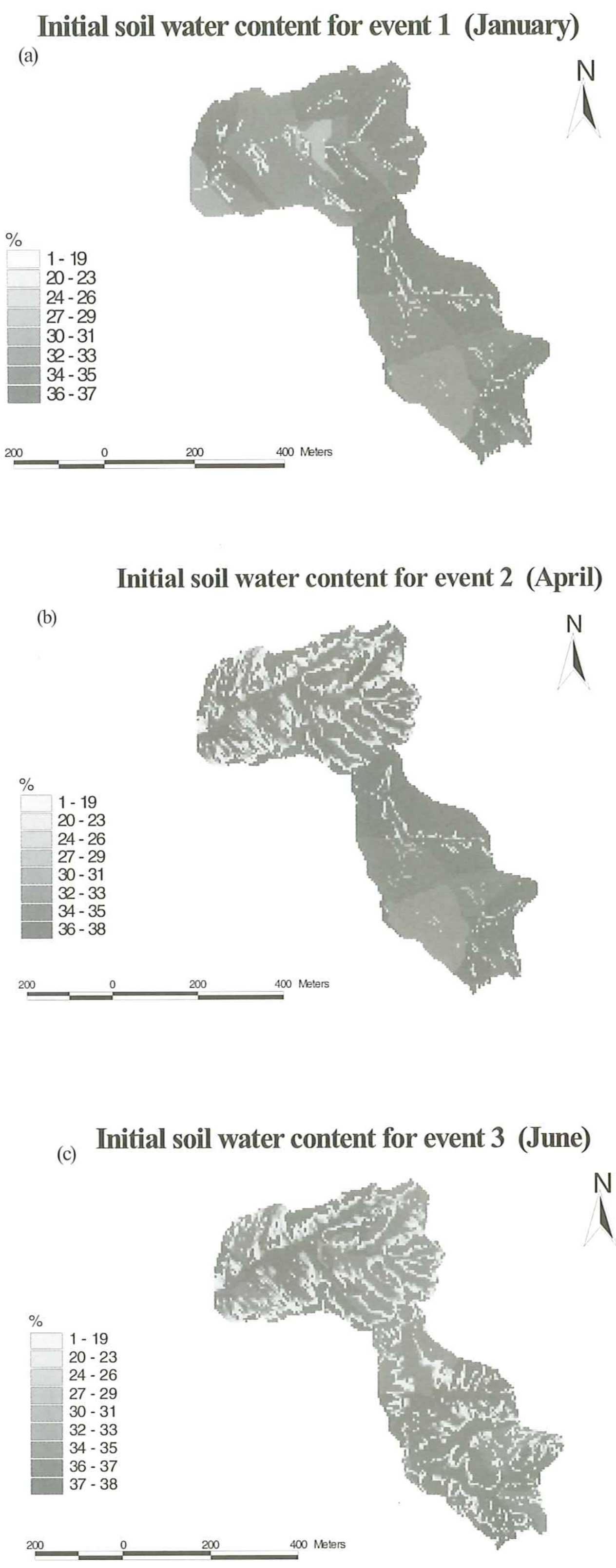


Figure 6. Pattern from surface to water table (min. depth in mm) for the three events (a) for low, (b) for high, and (c) for medium.

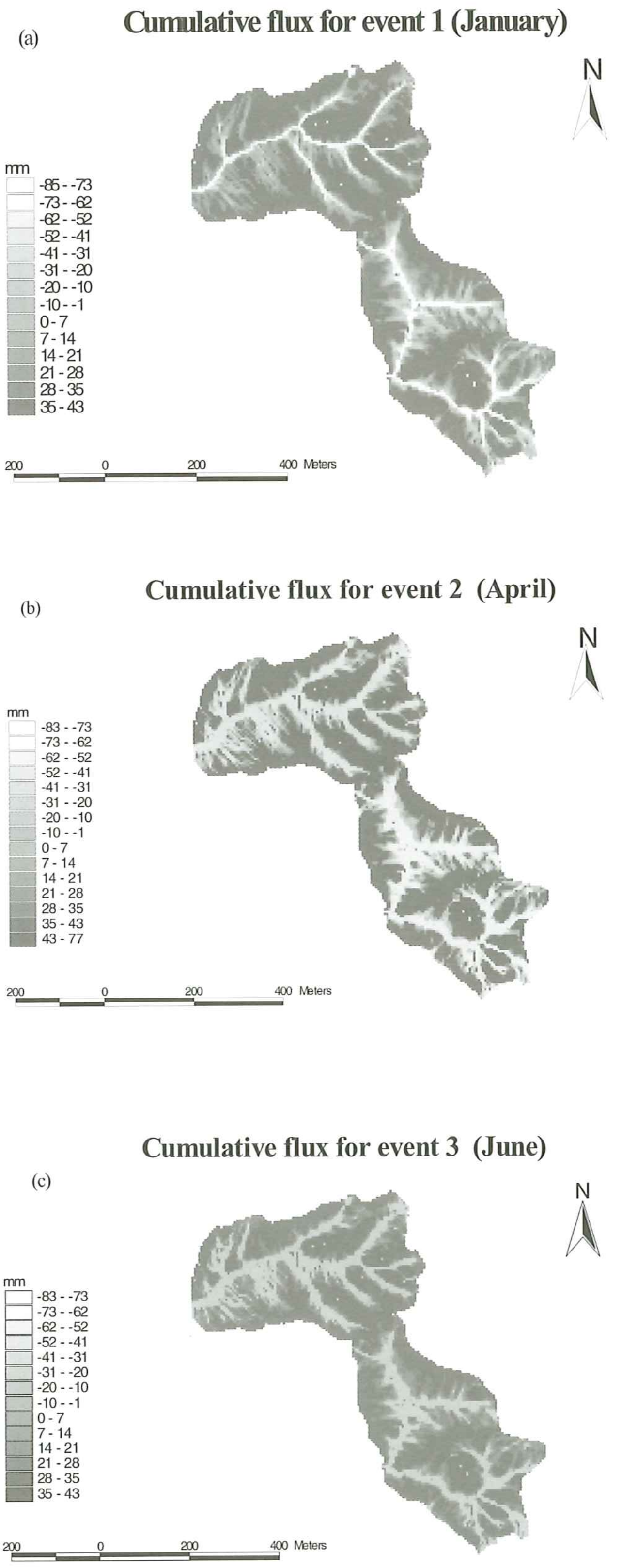


Initial soil water content for event 1 (January)

Initial soil water content for event 2 (April)

Initial soil water content for event 3 (June)

Figure 7. Pattern of soil water content between wilting point and saturation (% in the event).



Cumulative flux for event 1 (January)

Cumulative flux for event 2 (April)

Cumulative flux for event 3 (June)

Figure 8. Cumulative flux for the three events (mm of depth during the event).

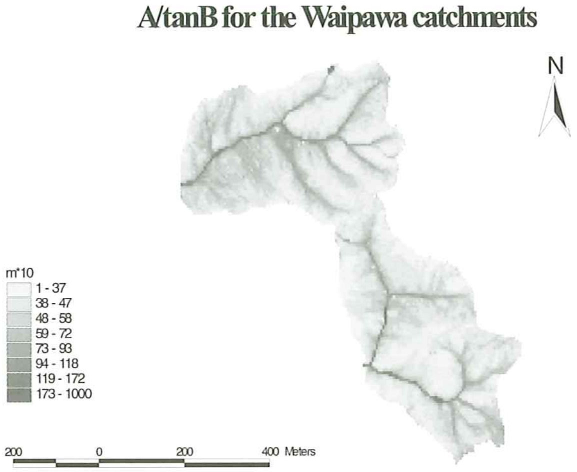


Figure 9. Topography index values (A/tanB) - in the unit of metres*10.

pixel. Values of the topography index A/tan$B$ at each location x indicate the likelihood of saturation. Large values of A/tan$B$ represent the locations within a catchment most likely to be saturated and to produce overland flow. These locations are topographically convergent and have gentle slopes and low transmissivity; that is, they drain a significant up-slope area of the watershed and have limited capacity to conduct water from the drained area in a down-slope direction. The areas likely to be saturated in the two Waipawa basins on the basis of topographic index value are shown in Figure 9. The pattern of A/tan$B$ is consistent with patterns of runoff-generating areas.

V. CONCLUSION

TOPMODEL has been successfully applied to the two catchments at the Waipawa fertiliser trial site. For the six-month calibration period approximately 84% of the variance in runoff was explained. The resultant values are considered realistic for the types of soil at Waipawa, given the assumptions of uniformity that have to be made. As a check on the calibrations, the models have also been used to simulate runoff for a period of record (July 1999) not used in the calibration process. Model validation showed that the model explained up to 67% of variance in the measured validation data. These results indicate that the model has been satisfactorily calibrated.

For three events during the calibration period, spatial information on the likely variation of catchment properties has been extracted and presented in map forms. These show a consistent and intuitively reasonable picture of how the catchments behave. For the summer event when conditions are dry, runoff is generated from areas close to the stream channel. As the catchments become wetter the areas of runoff generation around the channels enlarge. This indicated that surface runoff is being generated by the ground being saturated from below and being unable to absorb any rainfall.

ACKNOWLEDGEMENT

This research is partially supported by the New Zealand Foundation of Research Science and Technology and NASA. We are grateful to Alan Gillingham and Bruce Thorrold in AgResearch, New Zealand for their valuable discussions.

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