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A deterministic–empirical model of the effect of the capillary fringe on near-stream area runoff
2. Testing and application

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Abstract

The testing and application of HECNAR, a deterministic–empirical model that can account for the hydrologic effect of the capillary fringe on the near-stream area runoff, was carried out in several steps. The model was tested against the response of a laboratory model which resembled a near-stream saturated region of a cross-section, and the results of a field experiment. In each case, the simulated flow components were compared with the separated hydrograph components using a conservative tracer and the predictions of an unsaturated–saturated numerical model. The results were in reasonably good agreement. The model was then applied to a mine tailings site and the predictions were compared with numerical simulations, measured streamflows and the components of the stream hydrograph separated using ^{18}O as a conservative tracer. The predictions of HECNAR and the numerical model were in good agreement, as were the trends of the simulated and the measured hydrographs. However, some discrepancies existed between the measured and the simulated flows. This study shows that HECNAR is computer efficient and has a relatively modest input requirement. Incorporation of the model into a larger-scale and more comprehensive watershed model could provide a valuable tool to quantify total flows and runoff source components to the stream, in watersheds in humid environments.

1. Introduction

This paper includes the testing and application of a deterministic–empirical model that can simulate total streamflow and the components of the stream hydrograph in near-stream

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wetland regions, described by Jayatilaka and Gillham (1996). Testing and application of the model was carried out in several stages: (1) the capability of the model to account for the flow processes in the near-stream region (Zone 1) was tested against the response of a laboratory model and the results of the numerical simulations given by Abdul and Gillham (1984); (2) the applicability of the model to natural field sites was assessed by comparing the model predictions with the numerical simulations and the measured results of the field experiment at Borden reported by Abdul and Gillham (1989); (3) HECNAR was applied to a mine tailings site, and the results were compared with simulated flows given by the numerical model (Abdul, 1985), and the measured streamflows (Blowes, 1983) and the groundwater components were separated using ^{18}O as a conservative tracer.

The two-dimensional, unsaturated–saturated, finite-element model (Abdul, 1985), which was used for numerical simulations in the above steps, can simulate streamflows accounting for the effect of the capillary fringe mechanism. The model is similar to that described by Frind et al. (1976), but has been modified to allow for the generation and recession of a seepage face at the upper boundary. In addition, the model includes hysteresis in the unsaturated hydraulic parameters and compressibility of an entrapped air phase, and has been found to adequately represent the pertinent near-stream physical processes.

2. Testing of the model

2.1. Testing of the model against the laboratory results

Results of the laboratory experiments given by Abdul and Gillham (1984) were compared with the simulations of HECNAR. The experimental model consisted of a Plexiglas box (of 140 cm length, 8 cm width, and 120 cm height) packed with medium–fine sand with a uniform 12° slope on the upper surface, and a screened tube inserted at the toe of the slope to drain off free water, which represented the streamflow. According to the main drainage curve for the sand given by Abdul and Gillham (1984), the capillary fringe height of the sand was about 35 cm. Before rainfall, the water table was at the toe of the slope so that the triangular section of soil above the water table remained saturated, though under negative pressure. Two rainfall events, with intensities of 4.3 cm h^{-1} and 1.9 cm h^{-1}, respectively, were simulated, and chloride added to the rainwater was used as a conservative tracer to separate the measured streamflow into the pre-event and event water components. The simulated flow components of HECNAR were compared with the numerical simulations and the measured components given by Abdul and Gillham (1984).

2.1.1. Results and discussion

As the medium was fully saturated before the rainfall, HECNAR treated the entire cross-section as part of Zone 1, and, allowing for the generation of the seepage face, it represented the steady-state conditions of the physical model. Flows predicted by HECNAR, using a value of 0.005 cm s^{-1} for the saturated hydraulic conductivity of the sand (as given by Abdul and Gillham (1984)), are in reasonably good agreement with the measured results and those simulated by the numerical model (Fig. 1 and Fig. 2).

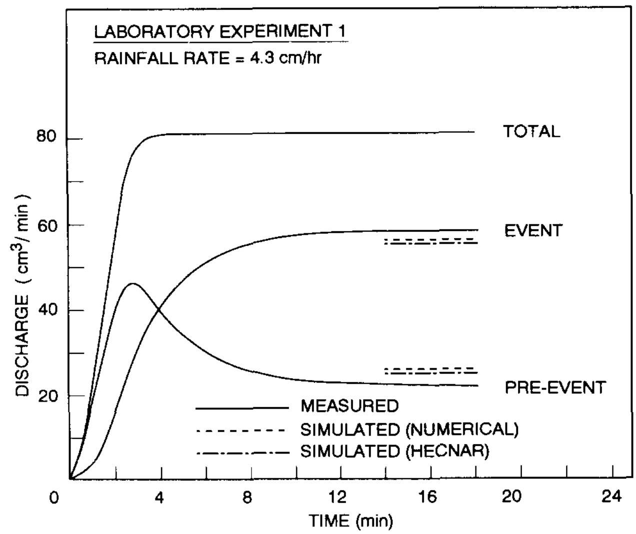

Fig. 1. Measured and simulated flow components of Experiment 1.

The rainfall in Experiment 1 supplied water at a rate of 40.13 $cm^3 min^{-1}$ at the recharge face, which extended laterally 70 cm from the outer boundary of the physical model toward the stream. The rainfall rate was more than adequate to supply the required recharge (24.99 $cm^3 min^{-1}$) to balance the subsurface discharge at the seepage face. The flow system was therefore handled by the high-intensity routine of HECNAR. In

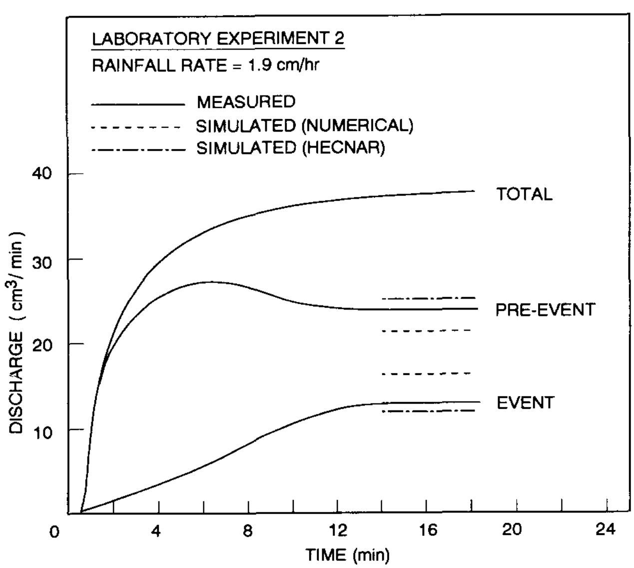

Fig. 2. Measured and simulated flow components of Experiment 2.

Experiment 2, however, as the rainfall intensity was below the limit defined for the high-intensity rains, the flow components were calculated by the low-intensity rain routine. In this case, over the recharge face, which extended 98.65 cm from the outer boundary, the water was supplied at a rate of 24.99 cm^3 min^{-1}, just sufficient to supply the recharge to meet the capability of the system to discharge groundwater. In the former experiment, results from HECNAR and the numerical model were almost identical, and in the latter HECNAR overestimated the groundwater component.

It should be noted that in this application of HECNAR, model parameters were physically measurable, and there were no trial-and-error adjustments. The reasonably good agreement between the simulated and measured results provides a degree of confidence in the validity of the methods used in HECNAR to approximate the flow system and to calculate the groundwater discharge to the stream.

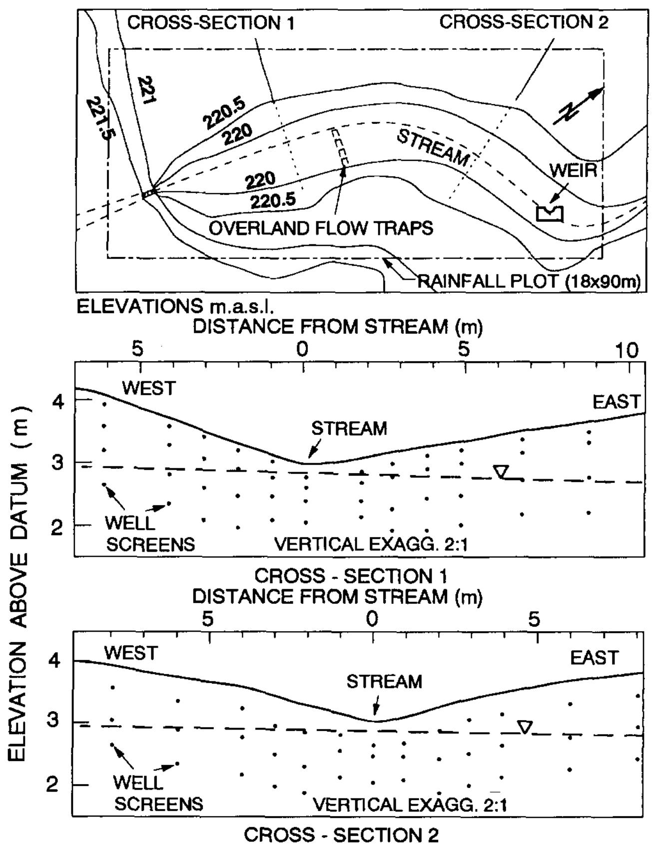

Fig. 3. Plan-view of the experimental site and schematic diagrams of Cross-sections 1 and 2 (from Abdul and Gillham, 1989).

2.2. Simulation of the field experiment at Borden

The field experiment at Canadian Forces Base Borden, Ontario, reported by Abdul and Gillham (1989), was carried out in a setting with hydrogeologic properties that can be considered to be uniform when compared with most naturally occurring systems. The study site, an area of 18 m × 90 m in a shallow sandy aquifer, was traversed by a man-made channel with a mean slope of less than 1° (Fig. 3), and the surrounding land was formed by shallow banks with slopes between 4° and 9°. A rainfall with an intensity of 2.0 cm h^{-1} was simulated by a sprinkler irrigation system, and bromide was added to the rainwater as a non-reactive tracer. Before rainfall, there was no flow in the channel and the water table was 22 cm beneath the channel at Cross-section 1. Details of the experimental design and monitoring of the physical response have been given by Abdul and Gillham (1989).

Assuming Cross-section 1 as a representative cross-section and taking the average slope of the section to be 6.5°, HECNAR was applied to simulate the streamflow and the components of the hydrograph. The saturated hydraulic conductivity of the soil was taken as 0.005 cm s^{-1}, and the porosity (0.37), the field capacity (0.09), and the air entry value for the sand (– 30 cm) were estimated based on the main drainage curve for the sand (Abdul and Gillham, 1989). A pore-size distribution index of 3.0 was used, and the delay index was set to zero at the beginning of the simulation.

The instantaneous streamflow hydrograph (Fig. 4) was obtained by multiplying the simulated lateral flows based on unit length along the stream, by the length of the reach (70 m). Fig. 5 includes the hydrograph obtained by routing the lateral flows along the channel to the downstream weir, according to the variable storage coefficient (VSC) routing procedure in HYMO—Hydrologic Model (Williams and Hann, 1973), using a

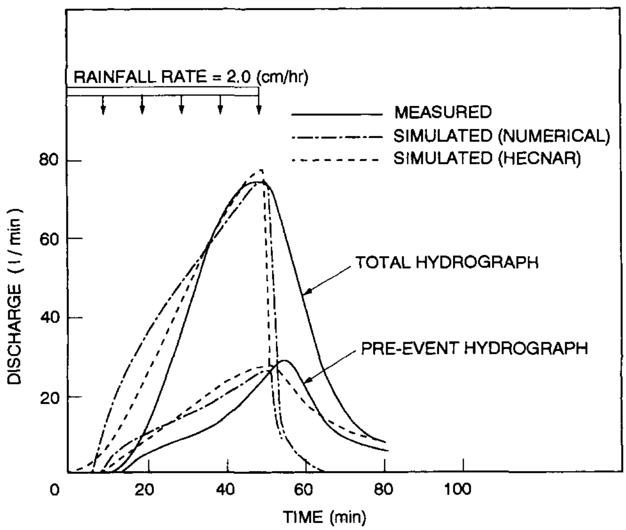

Fig. 4. Measured and simulated (instantaneous) hydrographs for the field experiments at Borden.

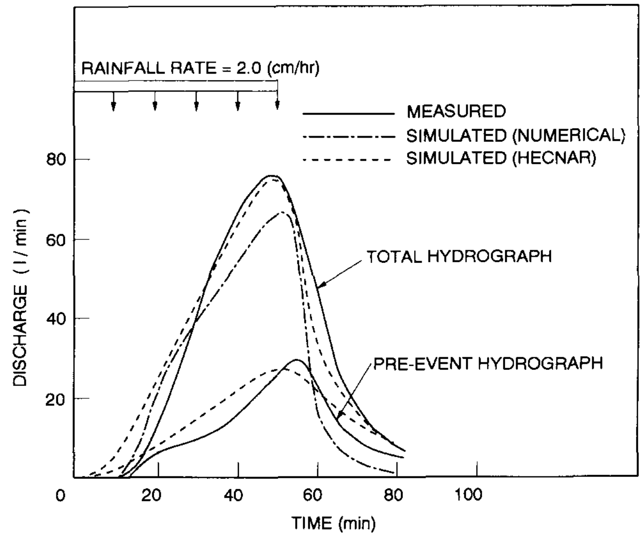

Fig. 5. Measured and simulated routed stream hydrographs for the field experiment at Borden.

channel slope of 0.17%, and Manning's roughness coefficients of 0.05 and 0.03 for the near-stream surface and for the stream channel, respectively (Chow, 1959).

2.2.1. *Results and discussion*

Based on the capillary fringe height (30 cm) and the initial water-table depth (22 cm), HECNAR estimated the lateral extent of the near-stream saturated zone (Zone 1) before the rainfall to be about 0.7 m on either side of the channel. The model simulated the gradual expansion of Zone 1 during the rain event, which at the end of the 50 min rain event, extended up to 1.9 m from the stream. At the beginning of the event, the effective specific yield in the soil columns (of Zone 2) closer to the stream were as low as 0.02 and 0.05, and increased gradually with distance from the stream to the maximum specific yield (0.28). Because of the low effective specific yield, which is an order of magnitude lower than the maximum specified, soil columns closer to the stream became saturated soon after the start of the rainfall.

Continued saturation of columns through the event moved the boundary line between Zones 1 and 2 a distance of 1.2 m in the up-slope direction. In the far-stream zone (Zone 3), overland flow was not generated, and this region did not participate in the generation of the stream hydrograph. The flow components to the stream were calculated by the high-intensity rain routine of HECNAR.

Without allowing for any delay in the water-table rise in Zone 1, the model would assume the water table in Zone 1 to rise to the ground surface with the onset of rainfall. Thus the entire Zone 1 would act as a flow generating zone and would produce high flows at the stream soon after the start of precipitation. However, streamflow did not occur until about 10 min after the start of rainfall. This indicates that, though the capillary fringe extended to the ground surface near the stream, the tension-saturated region did not act as a region with a zero specific storage capacity. Instead, probably because of the presence of macro-pore spaces owing to grass-root channels or worm burrows, or owing to the presence of the organic-rich soil layer, the rise in the water table was delayed at early times and thus the streamflow did not occur immediately after the onset of rain. To account for the effect of these conditions, the delay index was gradually increased, and the best match (the presented results) was obtained with a delay index of 40 min. It should be noted, however, that this was the only parameter adjusted to obtain the results of Fig. 4 and the rest of the parameters, which were assigned values as mentioned above, were not changed.

The simulated instantaneous, and simulated routed streamflow hydrographs of HECNAR are compared in Fig. 4 and Fig. 5 with the simulated results of the numerical model and the measured streamflows. The simulated and measured hydrographs are generally in good agreement, with the simulated routed flows showing a somewhat closer agreement with the measured flows. However, some differences are apparent, most of which can be explained considering the assumptions and the structure of HECNAR.

For example, the simulated hydrograph shows an early rise in the rising limb and a rapid decline in the recession limb, particularly in the instantaneous stream hydrograph. The model assumes that the excess rain occurring along the cross-section in a particular time interval arrives at the stream within the same time interval, whereas in the field, the excess rain would have to flow overland for some time before reaching the stream. Further, the model does not account for interception and depressional storages, which could behave as sources of water once the rainfall ceases. These factors could cause the prediction of high streamflows especially at early times, and a rapid decline in streamflow after the rain event. In addition, there is uncertainty concerning the degree to which the soil parameters used in the model are representative of the average field condition.

The simulated pre-event discharge (groundwater flow) hydrograph showed a rather uniform increase up to the peak flow rate, whereas the measured (separated using the tracer) pre-event hydrograph showed somewhat different rates of increase of pre-event water flow. This could be attributed to the fact that the model assumed a uniform slope of 6.5° to represent the surface slope, whereas the field slopes varied from 4° to 9°. As the saturation propagates up-slope during the event, the hydraulic gradient toward the stream could vary according to the surface slope, and this could cause variations in the pre-event water discharge to the stream as shown by the measured pre-event hydrograph.

The predicted pre-event (groundwater) flows of HECNAR show an overall reasonable agreement with the simulated flows of the numerical model and the measured flow. At the time of peak discharge, the predicted pre-event flow component of HECNAR accounted for 36% of the total flow, which is in close agreement with the pre-event discharge (38%) calculated from tracer separation of the measured flow (Abdul and Gillham, 1989). The close agreement obtained extends the confidence in the method used in HECNAR to estimate groundwater discharge to the stream that results from the transient flow system occurring during the rain events, and provides some evidence of the ability of the model to accommodate the dynamics of the near-stream flow processes.

2.3. Sensitivity of the model predictions to the delay parameter

The parameter for the delay in the water-table rise in Zone 1 is entirely empirical, and accounts for the time required for the water table to attain the elevation determined by the rainfall rate during an event at a given field situation. This is the only parameter in HECNAR for which there is not a physical basis, and its effect on the simulated results was examined through a sensitivity study of the simulations of the Borden experiment discussed above.

The simulated total and pre-event discharges corresponding to delay index (*d*) values of 0, 20, 40, and 60 min are shown in Fig. 6. Fig. 7 indicates the simulated flow hydrographs if the rainfall had continued with the same intensity (2.0 cm h^{-1}), up to 230 min. The results show that the simulated total flows, as well as the components of the hydrograph, are significantly influenced by the delay index at early times. However, the influence gradually diminishes with time, and given the event is sufficiently long the simulations become independent of the delay index.

The delay in the water-table rise is considered to occur as a result of the presence of some macro-pore spaces in the porous medium above the water table, within the capillary fringe, in the actual field conditions, instead of the completely saturated conditions assumed in the model. The effect of this condition would be such that, with the onset of precipitation, the water-table rise (to the elevation determined according to the intensity of rainfall), would be delayed until the medium is completely saturated. This would in turn result in lower discharge in the stream, as the lateral extent of the contributing region (in Zone

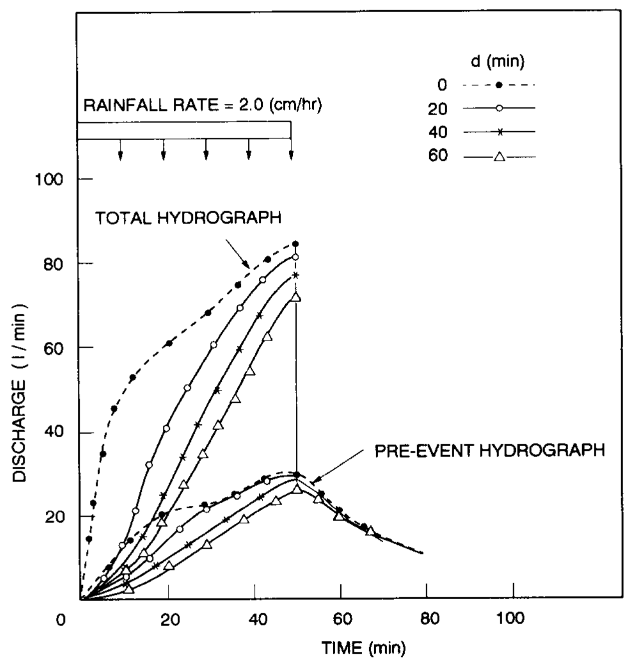

Fig. 6. Effect of the delay parameter (*d*) on the simulated (instantaneous) lateral flow hydrograph during short duration events.

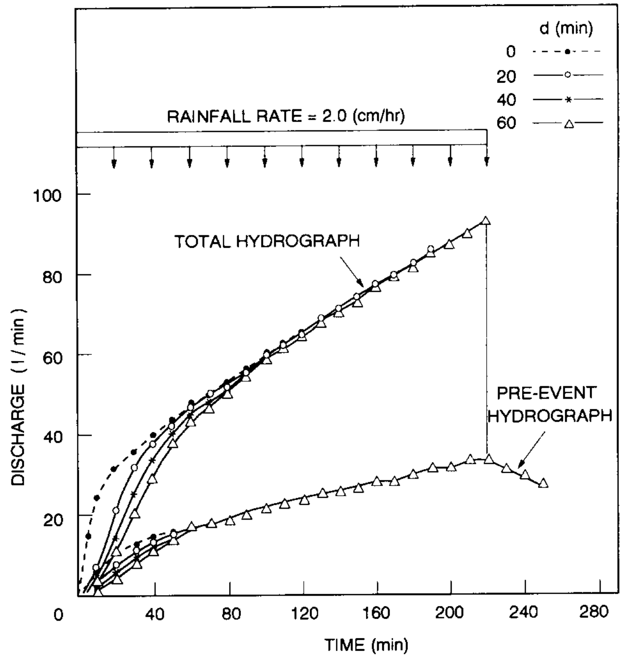

Fig. 7. Effect of the delay parameter (*d*) on the simulated (instantaneous) lateral flow hydrograph during long duration events.

1) would be less than that predicted according to the height of the capillary fringe. The delay index, which accounts for the initial storage capacity in Zone 1, would therefore reduce the flow in the stream at early times. As the event continues, the initially available storage spaces would gradually be filled, and the water table would more rapidly attain the maximum elevation (according to the rainfall intensity). Therefore, the reduction of the streamflow at early times and the decreasing influence of the delay index on the simulations with time shown in the results indicate that the delay index consistently simulates the presence of initial storage spaces in the near-stream saturated regions, in the natural (field) conditions.

Based on the results it can be concluded that, in long duration events, the use of a zero delay index would not significantly affect the model predictions. In short duration events, as the results could be substantially influenced by the delay index, its value should be estimated according to the field conditions. At present, this has to be done by calibrating the model. With further experience it may be possible to establish some guidelines to estimate the delay index according to the field conditions.

3. Application of the model

3.1. Application of HECNAR to the Pronto tailings site

The Pronto study site was located on the tailings produced from mining operations in

Elliot Lake, Ontario. The tailings impoundments in the Elliot Lake area have areas with shallow water tables, and are commonly traversed by perennial or intermittent streams. The pore water of these wastes contains high concentrations of heavy metals and radionuclides. Blowes and Gillham (1988) investigated the physical and chemical interactions between the groundwater and surface water in a tailings area, and showed that groundwater occurs as a significant component of streamflow, and represents an important pathway for the release of pollutants to surface waters. Even though the infiltration of rain water could displace the initial pore water of the tailings near the stream, continuing geochemical reactions maintain high concentrations of contaminants in the pore water. Therefore, tailings have a great potential to release contaminants to surface waters over long time periods.

In the development of management schemes for tailings impoundments which will minimise the release of pollutants to the environment, it is important to have an accurate runoff prediction technique. As the capillary fringe mechanism is considered to play an important role in the generation of streamflow in tailings areas (Blowes and Gillham, 1988), HECNAR could provide a reasonable predictive tool for evaluating the runoff characteristics of tailings impoundments. HECNAR was applied to the Pronto study site considering three storm events, during which the response of the study site was monitored as reported by Blowes (1983). At this site, measured streamflow hydrographs were separated using ^{18}O as a conservative tracer.

The study area (approximately 0.64 ha) was of very low relief, and was drained by intermittent streams originating in the westerly end of the area as shown in Fig. 8. The geologic material was silty sand, for which laboratory permeameter tests gave a saturated hydraulic conductivity value of 2.4×10^{-4} cm s^{-1}. This was reasonably consistent with the

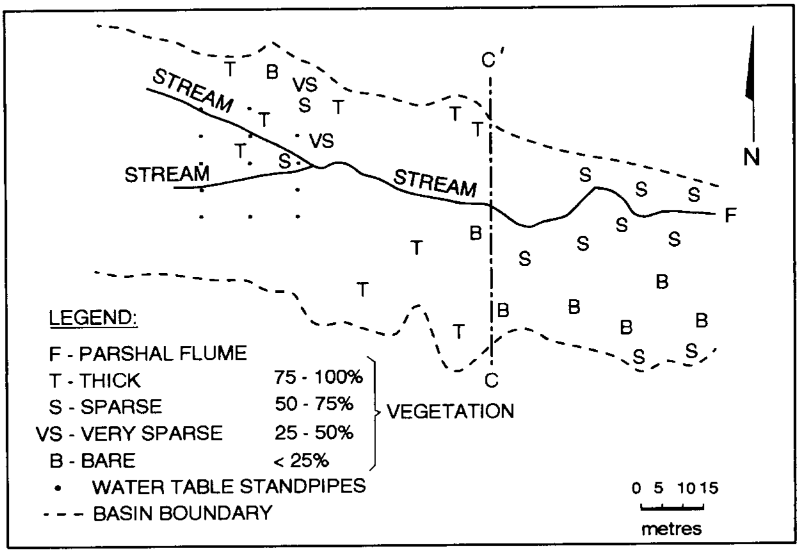

Fig. 8. Plan view of the Pronto study area.

results of bail tests conducted in piezometers installed at the site, which showed hydraulic conductivity to vary from 3.53×10^{-5} to 1.0×10^{-4} cm s^{-1}.

3.1.1. Simulation of streamflows

The streamflows during three rainfall events at the study site were simulated using HECNAR and the numerical model (Abdul, 1985), using Cross-section C–C′ (Fig. 8) as the representative section. Because of the very low relief, there was a good deal of uncertainty in attempting to locate the hydrologic boundaries for the reach of the stream being considered. The length and the width of the study area were taken as 160 m and 40 m, respectively, and one-half of the cross-section with a lateral distance of 20 m from mid-stream was used in the simulations. A near-stream slope of 3.5° to a distance of 3 m from the channel, and a far-stream slope of 1.5° were used to represent the surface slope of the section in HECNAR. The saturated hydraulic conductivity of the soil was taken as 2.4×10^{-4} cm s^{-1}. Based on the main drying curve of the soil (Jayatilaka, 1986), the height of the capillary fringe was estimated to be 80 cm. A porosity of 0.36, field capacity of 0.14 and pore-size distribution index of 1.6 were used in the simulations, and the delay parameter was set to zero.

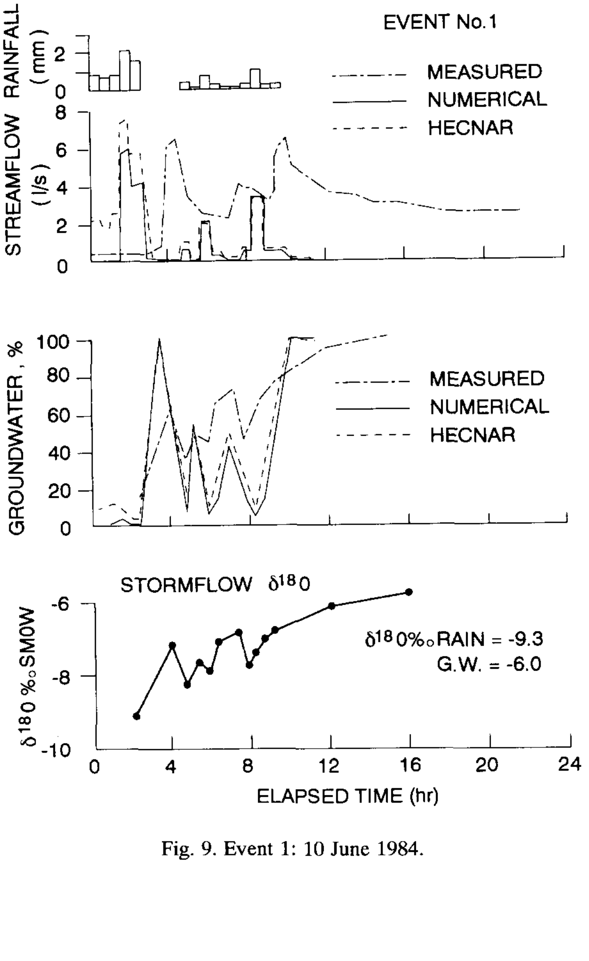

Fig. 9. Event 1: 10 June 1984.

In the numerical simulations, the depth of the cross-section at the stream and at the outer boundary was taken as 5.73 m and 6.1 m, respectively, and the section was discretised into 1600 triangular elements, having 891 nodes. The lateral and bottom boundaries of the cross-section were treated as impermeable, and an atmospheric boundary was assumed at the top. At the start of the rainfall, all the nodes on the top (atmospheric) boundary were assigned a specified flux calculated according to the rainfall intensity of each event. The simulations were carried out including hysteresis in the hydraulic parameters using the water content–pressure head relation for the soil material given by Jayatilaka (1986).

Figs 9–11 show the distribution of rainfall and the ^{18}O composition of storm flow during Storm Events 1, 2, and 3 respectively. In addition, the figures include the total streamflows and the groundwater components simulated using HECNAR and the numerical model, along with the measured streamflows and the pre-event (groundwater) components as a percentage of the total streamflow separated using the isotope mass balance technique described below.

3.1.2. Isotopic separation of hydrographs

The isotope method of hydrograph separation has been presented in detail elsewhere (e.g. Fritz et al., 1976; Sklash and Farvolden, 1979), and will be presented here briefly. One form of the hydrograph separation equation, as given by Fritz et al. (1976) is

$$Q_S = Q_T(d_T - d_R)/(d_S - d_R) \tag{1}$$

where Q_T is stream discharge, Q_S is pre-storm water (groundwater) component of the streamflow, d_T is ^{18}O content of streamflow, d_S is ^{18}O composition of groundwater (pre-event water), d_R is ^{18}O composition of rain water (event water). Thus, having measured values of Q_T, d_T, d_S and d_R, the groundwater component Q_S in the total discharge can be calculated.

In applying Eq. (1) it is assumed that: (a) the groundwater has a uniform isotopic composition; (b) the isotopic composition of the groundwater is significantly different from that of the rain water. Provided reasonable care is taken and samples are collected at sufficiently small time intervals, Q_T, d_T, d_S and d_R can all be determined with an adequate degree of certainty. However, evaluation of d_S can frequently be a significant source of uncertainty. The wide range shown in ^{18}O values (– 1.46 to –8.0‰) determined in the groundwater at the study site (given in Table 1) suggests that Assumption (a) given above is not met at this site. Preliminary calculations, using values within the range given in Table 1, showed that for a particular event, the groundwater component in the stream discharge could vary from near zero to in excess of 100%. The mean value of –5.69‰ gave reasonable results for some events, but groundwater values in excess of 100% for some portions of other events. This observation suggests that even over the relatively short period of this study, the effective groundwater ^{18}O concentration was not constant over time. Considering the variability shown in Table 1, one can speculate that the effective groundwater ^{18}O value would depend upon the groundwater zone that is contributing discharge, and this in turn could depend upon the hydrologic characteristics of a particular event. Alternatively, the effective groundwater ^{18}O could vary over time with successive displacements of the pore water.

In this study, the ^{18}O concentration in the streamflow that was determined long after the

Table 1
^{18}O composition of the groundwater samples

Distance from the stream (m)		Depth from ground surface (m)	^{18}O (‰)
Left	5	1.0	–5.96
	2	1.0	–6.27
Mid	0	0.5	–7.61
	0	1.0	–8.0
Right	2	0.5	–1.46
	5	1.0	–4.82

end of the rainfall event, where streamflow was almost certainly all groundwater, was used as the effective value. Though there is a degree of uncertainty associated with this procedure, considering the variability in the measured groundwater values, it was viewed as the most reasonable method of determining the effective d_S value. The values determined by this procedure (given below) varied from event to event, but in all cases were within the range of the measured groundwater values.

3.1.3. Event 1: 10 June 1984

Before precipitation, the water table was 32 cm below the channel at mid-stream of Cross-section C–C′. Because the capillary fringe height was 80 cm, Zone 1 extended to a distance of 14.3 m from the channel, and thus included a major portion of the section at the beginning of the event.

A total of 9.3 mm of rain, with an ^{18}O composition of –9.3‰, fell within about 10 h (Fig. 9). Based on the ^{18}O values of stormflow long after the cessation of precipitation, the groundwater ^{18}O value for this event was taken as –6.0‰. The total stream discharge and the groundwater component simulated by HECNAR are in good agreement with the simulations of the numerical model, and indicate a trend that agrees with the measured results. However, the measured stream hydrograph is displaced in time by about 2 h with respect to the simulations, and has higher flows later in the event, whereas the simulations show almost step changes in streamflow in response to changes in rainfall intensity, and the measured changes in flow are more gradual. In particular, the models show a sharp decline to near-zero values of streamflow shortly after the end of precipitation, whereas the measured hydrograph shows a long sustained recession limb.

The close agreement of the predictions of HECNAR with those of the numerical model indicate that HECNAR is giving a good representation of the perceived physical processes. Because both models represented the Borden experiment well, where the conditions were well defined, it is reasonable to suggest that the apparent discrepancies between the measured and simulated results could be a result of an incomplete description (or understanding) of the hydrologic conditions at the Pronto study site. It should be noted that a great deal of uncertainty was involved in the selected boundary of the study area, and the degree to which the selected cross-section is representative of the field situation is not certain, as the area is not drained by a single channel (Fig. 8).

In addition, several assumptions associated with HECNAR (as well as with the numerical model) may have contributed to the differences between the measured and the simulated results. In particular, the models assume the rainfall in excess of infiltration (and recharge) along different regions of a cross-section to flow overland to the stream, and the overland flow of event water to end immediately at the end of precipitation. As a result of very low relief, substantial depressional storages were noted during the rainfall events. At the end of precipitation this storage would have acted as a source of water, and could have supplied the recharge required for the discharge of subsurface water during recession periods. This could cause a more gradual recession than that simulated; however, this process alone cannot be expected to produce observed streamflow rates during recession periods in the events considered at this site.

During this event, the total rainfall volume over the study area was 59.5 m^3, and the simulated total streamflows were 54.3 m^3 (HECNAR) and 31 m^3 (numerical model) at the end of the simulation period (11.2 h). Based on the apparent response of the streamflow hydrograph to rainfall, the measured streamflow over an 11.2 h period was estimated to be 147.25 m^3. In addition, a streamflow of about 2 $l\ s^{-1}$ continued over a period of more than 6 h. Considerably higher discharge volumes in comparison with the total volume of rainfall were recorded during this and the following two events at this site. Reasons for these observations are not known. However, as the flume was not calibrated at this site, the absolute values of the measured discharges are uncertain, though the streamflow records should provide relative flows in the channel accurately. Therefore, the trends shown in the measured flows rather than the absolute flow values were considered to be more reasonable for comparisons with simulated results.

Though the trends are similar, differences between the measured and the predicted groundwater components are also apparent. It should be noted, however, that the accuracy of the results of the hydrograph separation depends on the degree that the ^{18}O values used in eqn (1) represent the actual ^{18}O composition of groundwater, rainfall and streamflow at a particular time. The isotopic composition of rainfall could vary within a rain event, and as discussed above, the groundwater contribution may have different isotopic values within an event.

The predicted groundwater component of HECNAR is highly sensitive to the intensity of rainfall. However, the available rainfall records only provide the accumulated rain during a particular period. Thus the input supplied to HECNAR was the average rainfall rate during the period, and hence the predictions would be the average total streamflow and the average groundwater component within the rain period.

As heterogeneous and anisotropic conditions are normally associated with the tailings, a degree of uncertainty is involved with the saturated hydraulic conductivity and other soil parameters used in the models to represent hydraulic properties of the tailings material. The hydrologic uncertainties of the Pronto tailings site, the complicated nature of the rainfall events, and the other points highlighted above should be taken into account in evaluating the simulated results of HECNAR in this event and the following rainfall events.

3.1.4. Event 2: 12 June 1984

Before precipitation, the depth to the water table at mid-stream of Cross-section C–C′ was 18 cm and there was no channel discharge. A total of 9.8 mm of rain, with ^{18}O

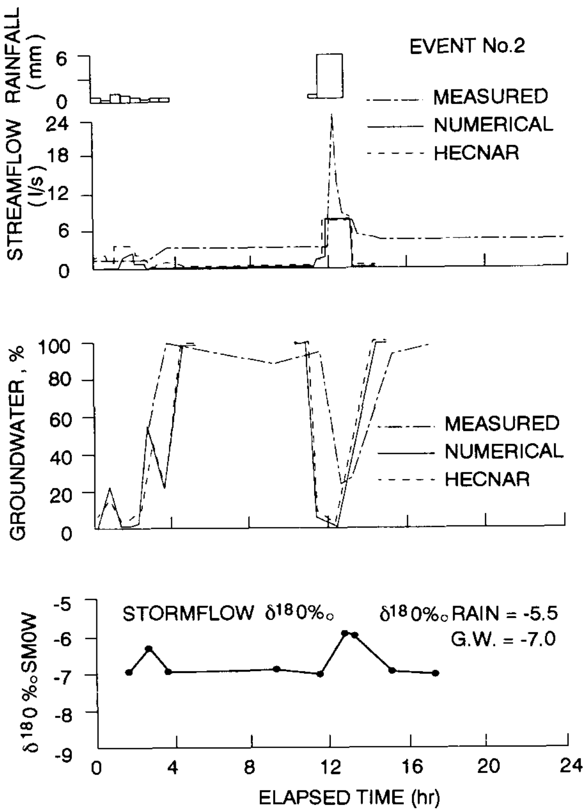

Fig. 10. Event 2: 12 June 1984.

composition of rain −5.5‰, fell in two periods which were 7 h apart (Fig. 10). ^{18}O content of groundwater during this event was taken as −7‰. Although during the early rain period HECNAR predicted somewhat higher flows than the numerical model, in general, the simulated total streamflow and the groundwater components of the two models agree closely. The measured hydrograph indicates a sharp peak of about 25 l s^{-1} during the high-intensity rain period, whereas the predictions indicate a flow rate of 8.1 l s^{-1}. It is possible that the high measured flow was the result of a short period of very intense rain that, because of the sampling frequency, was not reflected in the rainfall record. During the inter-storm period and after storm periods flow of about 5 l s^{-1} persisted in the channel, whereas the models indicated near-zero discharge.

At 14.1 h after the beginning of rainfall, measured streamflow volume was 190.7 m^3, whereas the total rainfall volume over the study area was 62.7 m^3, again showing an inconsistency as in the previous event. The simulated streamflow volumes by the numerical model and HECNAR were 65.1 m^3 and 74.4 m^3, respectively. In spite of the obvious differences from measured flows, prediction of the models for both total flow and the groundwater contribution to flow are similar.

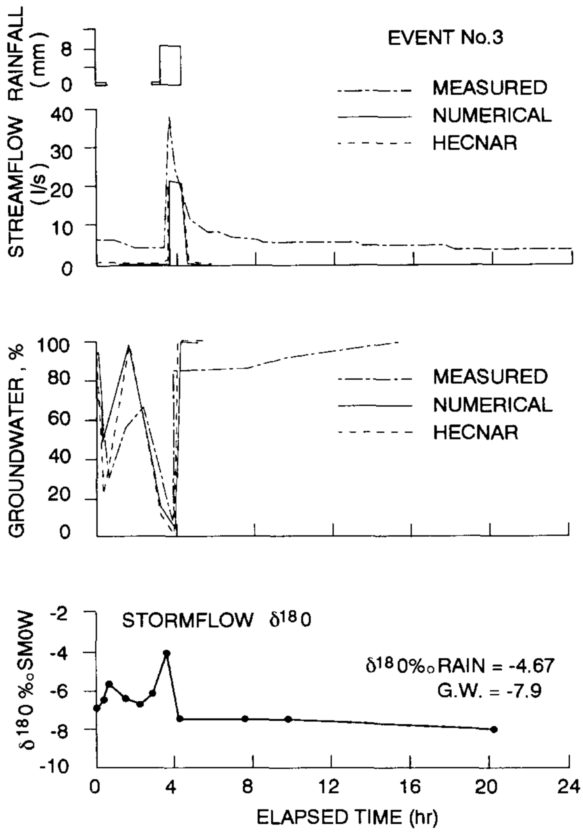

Fig. 11. Event 3: 13 June 1984.

3.1.5. Event 3: 13 June 1984

Before the onset of rainfall, the water table was high, about 2 cm below the base of the channel, and a base flow of 0.204 l s^{-1} was observed in the channel. During the event, a total of 9.2 mm of rain with an isotopic composition of −4.67‰ fell over a period of about 4 h (Fig. 11). For this event, ^{18}O value of the groundwater was taken as −7.9‰.

As in the previous events, predictions of HECNAR were in good agreement with the numerical simulations, and the trend in the simulated results shows good agreement with the measured results. At 5.9 h after the beginning of the event, predicted total streamflows were 62.1 m^3 (HECNAR) and 54.4 m^3 (numerical model). Measured streamflow volume, 202 m^3 (at 5.9 h), was again considerably higher than the total rainfall volume of 58.9 m^3.

3.2. Discussion

At the Pronto study site, predictions of HECNAR indicated a close agreement with the numerical simulations, and the measured and simulated trends were generally in good agreement. However, discrepancies were apparent between the simulations and the measured results. The hydrologic uncertainties at the site, the assumptions associated with the models, and the hydrologic processes not represented in the models could all have contributed to the differences. The most striking differences were the higher measured and more persistent streamflows than predicted. Though these differences may well have been the result of uncertainty concerning the watershed boundaries, the precise reasons for the differences remain unclear.

The isotope hydrograph separation at this site indicated that the isotopic composition of the groundwater contribution could vary during periods as short as a few days. Thus in near-stream shallow water-table regions, the variation of the tracer composition of groundwater could introduce a significant error in the use of the isotopic hydrograph separation technique.

It should be noted that the predicted groundwater component of HECNAR at this study site during low-intensity rain periods was as high as 50% of the total streamflow (Event 1), was in agreement with the results of the numerical simulations (53%), and was consistent with the measured values. Predictions of many existing models, which do not account for the near-stream area runoff processes, would not indicate the occurrence of such a high groundwater component. It is important that a model such as HECNAR, with the capability to quantify runoff-source components adequately, is used for predicting streamflow in field situations where the groundwater discharge to the stream represents an important pathway for the release of pollutants to surface waters.

4. Computer requirement of the models

The computer requirement of HECNAR is compared with that of the numerical model (Abdul, 1985) using the simulated events at the Pronto study site. For the three events considered the array requirements of the numerical model and HECNAR were 220 760 bytes and 472 bytes, respectively, and the execution times of the numerical model varied from 2359 to 4797 times that of HECNAR. Both programs were written in FORTRAN, and were run using a WATFIV interpreter on a IBM 4341 mainframe, CPU running under VM/CMS.

This shows that the required array area and the execution time of HECNAR are low in comparison with those of the numerical model. Large computer time and storage requirement is typical of numerical models, as the domain has to be discretised into finite elements, and a large number of elements and nodes have to be handled by the model. Despite the accuracy in the representation of the physical processes of a system, the general applicability of the numerical models as predictive tools at the field scale is hindered by the high cost of application. On the other hand, HECNAR has been shown to provide reasonably close predictions to the numerical simulations, but with the use of low computer time and storage. From the low cost and the relatively modest input requirements, the incorporation of HECNAR into larger-scale and more comprehensive watershed models should be a practical pursuit.

5. Summary and conclusions

The good agreement obtained by testing HECNAR against laboratory results and numerical simulations provided a degree of confidence in the method used in the model to account for the flow processes associated with the near-stream saturated region. In particular, the routines used to calculate the groundwater component to the stream during both high- and low-intensity rains appeared to be adequate.

At the Borden study site, the predicted total flow and the groundwater flow components were in good agreement with the predictions of the numerical model and the measured results. This enhanced the confidence in the methods used in the model to account for the near-stream flow processes.

In the application of the model to the Pronto study site, the results of the model were very similar to the numerical simulations, providing further evidence that the empirical model gives an accurate representation of the physical processes that were incorporated into the model. Both the numerical model and empirical models gave trends that were similar to the measured results; however, marked and consistent differences were evident. In particular, both the numerical model and HECNAR failed to simulate the long tail of the recession limb of the hydrograph, and both significantly underestimated the total discharge. However, it should be noted that the measured total discharge exceeded the volume of precipitation that falls, suggesting that the contributing area was larger than assumed, or that the discharge measurements were inaccurate. Thus, it is reasonable to suggest that the observed differences between measured and simulated results were, at least in part, a consequence of uncertainties in the physical characteristics of the watershed, and are not necessarily the result of inadequate approximations in the models.

Though not part of the original objectives, the use of the isotope hydrograph separation method at the Pronto study site showed that the isotopic composition of groundwater in shallow near-stream regions could vary spatially, and possibly over short periods of time. This variation could lead to significant error in the use of isotopic methods to separate the components of the hydrograph.

The model was found to be computer efficient in that, with the use of very small computer time and storage, it provided predictions similar to the results of the numerical simulations. The input requirements of the model are much less elaborate than for the numerical models and for most empirical models. Few parameters are required, and these can generally be determined from relatively straightforward physical measurements. Unlike many models, only one parameter, the delay index, is obtained through calibration.

HECNAR was designed to account for flow processes in the near-stream wetland regions that occur in response to precipitation. It does not include the hydrologic processes that are generally included in watershed models such as interception, evapotranspiration, depressional and detention storages, routing of overland flow, and the percolation of infiltration into the groundwater zone. By superimposing HECNAR on an existing model that considers these processes, an improved accuracy in predicting total streamflows and the runoff source components in watersheds with shallow water-table areas may be obtained.

Further studies on the response of the near-stream water table to precipitation would enhance the understanding required to improve the elements of HECNAR. To make it more suitable for field application, the areas of the model which need modifications are:

1. The representation of the ground surface slope of the near-stream area.

2. The flow component in the up-slope direction (from the near-stream saturated region to the far-stream region) that occurs as a result of the hydraulic gradient caused by the water-table mound.
3. The incorporation of effects of the changes in the stream stage and the conductance of the stream bed material on groundwater discharge.
4. The representation of the antecedent soil moisture conditions in the far-stream area.
5. The estimation of the delay parameter which accounts for the delay in the response of the water table in the area that remains tension saturated before precipitation. This may eliminate the calibration requirement of the model completely.

With these modifications and improvements, HECNAR may provide a valuable tool to quantify the total flows as well as runoff source components to the stream, when incorporated as a submodel of a watershed model. The present version of HECNAR has demonstrated a reasonable potential in this respect.

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