Runof97: a GIS-based, Distributed, Surface-Runoff Model

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Runof97 is a fully distributed Geographic Information System (GIS)-based surface runoff model. The model was built to assist the Daisy Lake Watershed Restoration Project. Daisy Lake and its surrounding watershed, located near Sudbury, Ontario, have been adversely affected by local mining practices, resulting in a severely denuded landscape, and acidic lake and soil conditions. The restoration project is studying the effectiveness of watershed liming to improve runoff water quality. By simulating overland flow, Runof97 will develop a better understanding of water/lime contact time on different surfaces, and will determine surface runoff velocities to assist with erosion studies, to help assess the degree of reforestation required to slow erosion, and to assess how lime of different grain sizes is redistributed. The model employs a block-centred, finite difference approach to solve its governing equation. The governing equation is an adaptation of the Manning equation for surface flow, and includes surface slope, surface roughness, and depth of water flowing over the watershed at any given time. Runof97 is capable of simulating varying rainfall intensity and infiltration rates during single storm events. The model accepts IDRISI images as input. The model was tested by comparing simulated and measured hydrographs at the outlet of the watershed for a small storm. The model simulated the timing and volume of two early peaks in the measured hydrograph. A third peak was not simulated but the peak probably results from interflow, which Runof97 does not

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address. Secondary purposes of the model are related to the visual capabilities of GIS. These include using the simulated surface water depth maps to test Digital Elevation Model (DEM) integrity, and the development of a "movie" of surface water flowing down the watershed. This dynamic visual display provides a more intuitive knowledge of water movement over the landscape.

6.1 Introduction

6.1.1 Daisy Lake Rehabilitation Project

Daisy Lake (46°27' N, 80°53' W) is a 36.1 ha lake located near Sudbury, Ontario. Daisy Lake is the site of an on-going project to study the effectiveness of watershed liming to improve watershed runoff water quality. The lake and surrounding watershed (284 ha) have been adversely affected by local mining practices, resulting in acidic lake and stream conditions (pH 4.13 - 5.19), high concentrations of Al, Ni, and Cu (Kaliczak, 1992; McCaffrey, 1993), and a denuded landscape.

Subwatershed J, located at the northeastern end of the lake, has become the focus of the rehabilitation project. The subwatershed covers an area of 37.9 ha. It is made up of over 50% barren land, with significant exposed bare rock (quartzite), and mudflats concentrated in the higher elevations. Where soil is present, it is generally shallow, with an average depth of less than 50 cm. Soil concentrations of Ni, Cu, and Fe are toxic (Lozano and Morrison, 1981). Soil pH values measured in 1992-93 vary from 3.67 to 4.44. The geology, vegetation species, vegetation density, soil textures, and soil depths of subwatershed J have been mapped in detail and digitized. Hourly discharge data is collected at the main stream of subwatershed J.

Identified needs within the Daisy Lake project include a fuller understanding of surface hydrologic processes, and the development of a predictive tool to assist with watershed-liming work. Runof97 was developed in response to these needs. Runof97 simulates surface runoff processes within the conceptual framework of overland flow. This is justified because roughly 50% of the watershed is bare rock. In natural, vegetated watersheds it has been argued that runoff occurring as overland flow is rarely observed. Instead, most of the rain water that reaches the ground is believed to infiltrate and then travel downslope as interflow or baseflow. However, there is little question that surface runoff does occur on barren and impervious surfaces. Watersheds adversely affected by deforestation, urbanization, or mining practices often consist of significant barren land and exposed rock surfaces. Therefore, overland flow may be expected to play a significant role in the hydrologic cycle at Daisy Lake, and this makes overland flow a valid conceptual approach for the model.

Runoff97 produces runoff water depth maps for the watershed surface, and simulates the runoff hydrograph for the watershed outlet. The purpose of the model is to study the effect of spatially varying watershed characteristics such as slope and vegetation patches on surface erosion processes and distributed watershed liming. These depend primarily on surface water velocity, which can be calculated from the water depth maps. The runoff hydrograph, from which lumped hydrologic characteristics including peak and total discharge can be calculated, is used to test the model. However, the hydrograph describes stream discharge due to overland flow only. Thus it will underestimate total discharge, even in largely impervious watersheds. This increases the difficulty of testing the model, but does not interfere with the use of the model for land-based purposes. The following chapter presents information on model design and testing. It does not include application results.

6.1.2 GIS-based Hydrologic Modeling

There are three ways to link a hydrologic model with a GIS: (i) use an interface program; (ii) build the hydrologic model directly within a GIS; or (iii) link the two separate systems by embedding the code of one into the other. The method chosen generally depends upon the relative time frame of development of the GIS database and the hydrologic model, and the level of sophistication of the hydrologic model.

Interface programs were used in the first integrations of hydrologic models and GIS, and they are probably still the most commonly applied linking method. Interface programs are used when it is necessary to link two pre-existing systems. They convert the spatial data stored in a GIS into a format compatible with a hydrologic model. HECAD is an example of an early interface model built to link HEC-1 with the GIS ADAPT (Davis, 1978). Another example is ArcView, which can be used to process ARC/INFO coverages for input into hydrologic models. Once the coverages have been processed, they are converted to the file format required by the model via scripts (macros) which are written by the user in Avenue, ArcView's object-oriented programming language (Shamsi, 1998). Other recent interface programs capable of linking several different GIS and models have also been developed (Kopp, 1996).

A second linking option is to build the hydrologic model directly within the GIS. In this method, the hydrologic model is built exclusively with tools available in the GIS and there is no separate hydrology program. Most GIS only allow for the incorporation of simpler models such as DRASTIC and TR55. But at the extreme end of this GIS-centric integration method are dynamic GIS- modeling languages in which the user can write a customized complex hydrologic model directly in a GIS computer language code that is relatively user-friendly. PCRaster is an example of such a GIS- modeling language (Van Deursen and Wessling, 1996).

The third type of linking mechanism involves operating with both a GIS and a separate hydrologic model, but the code of one program is directly embedded into the other. Usually, it is the GIS routines that are embedded into the hydrologic program, thus allowing the hydrologic model to access GIS data directly. This method eliminates the need for interface programs, and in this regard, speeds up the modeling process. The embedding method is often chosen when data are already in GIS format, a new hydrologic model is being developed, but the GIS is not sophisticated enough to build the model exclusively with GIS tools (Kopp, 1996). Runof97 falls into this third category. The GIS database already existed at the time the model was developed, and hence the hydrology model was written to read and write data files in IDRISI format.

6.2. The Model

6.2.1 Runof97 Description

Runof97 is a fully distributed model, and hence it is capable of incorporating spatially varying watershed characteristics, such as land cover and slope, which may have a significant impact on hydrologic responses to storm events. While accounting for spatial complexities, Runof97 accurately simulates surface runoff with a minimum number of required input parameters, making it a relatively easy model to implement.

The model operates in a windows environment and is fully menu driven. It produces runoff hydrographs for single rainstorm events, and can accommodate varying rainfall intensities and varying infiltration rates. Only surface runoff processes are simulated. Infiltration is accounted for, but the model does not simulate subsurface flow.

Runof97 is a block-centred, explicit, finite-difference model. That is, the storm event to be modeled is divided into many small time steps, and the watershed into many small blocks or cells. An iteration of the program is run for each time step, and the amount of water leaving each cell during a given time step is calculated based on the water depths in each cell in the previous iteration, plus the rainfall and minus the infiltration that occurs over the given time step. The water leaving each cell is then moved downslope as directed by a flow direction map, which is generated from a digital elevation model (DEM). Water travelling in a diagonal downslope direction can be split into three parts that flow into the three nearest neighbours, thus generating a more diffuse flow path over the landscape. Further generating a more realistic flow path, cell dimensions are corrected for slope; that is, the distance water travels across a cell is not the cell length, but the actual topographic distance.

The model applies the kinematic wave approximation to the full St. Venant equations governing shallow water flow and thus, the governing equation is an adaptation of the Manning equation, given below:

$$Vol_{out} = \frac{S^{1/2}}{n} D^{5/3} \frac{\cos \theta}{A} L W t_c \quad (6.1)$$

where:

- V_{out} = volume of water leaving a cell
- S = slope;
- n = Manning's roughness coefficient (dimensionless);
- D = water depth (mm);
- $\cos \theta$ = pathlength correction for slope
- A = actual horizontal path (L, W, or Diagonal)
- L = cell length (m);
- W = cell width (m);
- t_c = time step (sec).

The application of the kinematic approximation and accompanying use of the Manning equation to describe overland flow has been shown to give very accurate results and is widely used in hydrologic modeling (Liggett and Woolhiser, 1967; Onstad and Brakensiek, 1968; Akan, 1985; Akan, 1986; Moore et al., 1991; Muzik, 1996; De Roo et al., 1996). The main assumption of the kinematic wave approach is that the friction slope of a surface is equal to its surface slope (Wooding, 1965; Vieira, 1983). This assumption allows for the simplification of the St. Venant momentum equation to a form that is essentially the Manning equation, modified to represent shallow overland flow.

6.2.2 Runof97 Input

The model requires several IDRISI map layers as input, including a surface texture map, a slope map, a flow direction map, an infiltration map, a stream map, and depending on how the program is run, a water depth map. The surface texture map represents the constant term in the governing equation, and is described mathematically as $S^{1/2}/n$ where S = slope and n = Manning's roughness coefficient. This surface map is created in IDRISI using overlay commands. The roughness map used in its production is a map of landcover reclassified according to the corresponding value of Manning's roughness coefficient for each landcover type.

The slope map is a map of slope in rise/run, generated from a DEM. The map is incorporated into the surface texture map, and is also required as an independent input for the correction of flow distance across the cell from a map distance to the actual topographic distance.

The flow direction map is also generated from a DEM. The model uses this map to direct water flowing out of each cell to its downslope neighbour(s). In addition, this map is used to check whether cells are inside the watershed (value > 0) or outside, in which case the program simply moves on to the next cell.

The infiltration map is a map of infiltration rates according to land cover. Runof97 also has the option of modeling runoff with zero infiltration. Variable infiltration rates during a storm can be simulated by substituting different infiltration maps for different segments of a storm.

The stream map is a map of the streams within the watershed. It is required to identify cells for which diagonal flow should not be split when transferring water to downslope neighbours.

Storm rainfall data are entered as a lookup table. The table consists of three columns. The first two columns specify storm segment start and stop times, and the third column lists the depth of rain that fell during each time segment. Surface storage is accounted for by manually subtracting the storage depth from the total storm depth, such that the first storm segment begins once the storage depth is satisfied. The program automatically calculates the amount of rain that falls per iteration time step based on the information in the rainfall table.

In addition, the program requires a water depth map. This map can either be calculated by the program itself or can be provided to the program by the user. At the beginning of a storm, it is usual to let the program calculate the depth map, which then consists of a uniform depth in all cells, equal to the rain that would fall in the first time step. Thereafter the program updates the depth map with each iteration, by adding water depth flowing into each cell, subtracting water flowing out, subtracting water depth lost to infiltration, and adding rain to each cell as dictated by the rainfall table. Alternatively, when the program has been interrupted, as is done when a series of depth maps are wanted for different stages of the storm, the program can be started with the previous depth map, allowing the storm to continue from where it left off.

Other inputs the model requires are the total number of rows and columns of the IDRISI maps, cell dimensions, the cell address for the pourpoint (the cell that receives all watershed water), and length of the iteration time step.

6.3 The Test Storm: First Test-run of Runof97

6.3.1 Discharge and Rainfall Data

Hourly discharge (m^3/s) for the main stream of subwatershed J was obtained from the Ontario Ministry of Natural Resources (MNR). The MNR developed a water level-discharge curve for the main stream of subwatershed J, based on water level (m) and discharge (m^3/s) readings taken at the stream in September 1994. Hourly

stream levels have been recorded from September 1994 to present. Discharge data for the test storm of May 10, 1996 were taken from this database.

Rainfall data for the May 10, 1996 test storm were collected at subwatershed J of Daisy Lake. Readings were taken at four intervals over the course of the 8.5 hour event (Figure 6.1). This is the only storm for which rainfall data has been measured at subwatershed J.

Figure 6.1 Rainfall data for the test storm at subwatershed J on May 10, 1996. Surface storage was assumed to retain 10.0 mm, leaving 0.8 mm for the simulated runoff event.

6.3.2 Input Parameters

The subwatershed J maps have 275 columns by 311 rows, with each cell being 3.5 m wide and 4.5 m long. The watershed itself covers 31,169 of the 85,525 total cells in each map. The landcover map (Figure 6.2) shows that vegetation covers 45% of the area and 53% is bare rock. The vegetation is a sparse cover dominated by coppiced birch trees (*Betula papyferia*) with an understory composed primarily of birch seedlings, a patchy groundcover of moss (*Polia nutans*) and a grass (*Deschampsia flexuosa*) (Grosso, 1994). The bare rock areas include small patches of mudflats, scree and occasional clumps of grass (*Agrostis scabra*) or *P. nutans*.

The infiltration rate for bare rock was approximated by the permeability of quartzite (Freeze and Cherry, 1979), the bedrock underlying all of subwatershed J (Table 6.1). It seems likely that infiltration is actually higher on these rock areas since the rock is quite fractured with a fault along the main stream, but since there are no measured data available, the standard value was used. Pearce (1973) measured the infiltration rates for Sudbury glaciolacustrine silts and found that infiltration at the beginning of storms was commonly 6 - 20 mm/hr, declining to

Figure 6.2 Landcover in subwatershed J. (Light grey = vegetation; mid grey = bare rock; black = streams. The entire image is 760 m across and 1400 m long).

2 mm/hr after about 24 hr. Since much of the test storm surface runoff occurs between 8 - 24 hrs, an intermediate value of 4 mm/hr was selected for initial runs. Streams were assigned an arbitrary value of 0.01 mm/hr.

The roughness coefficient (n) for vegetated areas was assigned a value of 0.35. This value was determined by Pearce (1973) for Sudbury glaciolacustrine silts. Initially, bare rock and stream roughness coefficients were approximated with an asphalt value (0.0125) taken from Engmann (1983). A few trials were run using different values to calibrate the model, an approach used by Engmann. This resulted in much higher values for the bare rock areas (Table 6.1), similar to those for rangeland. This seems appropriate since the rock surfaces are much rougher than smooth asphalt, with occasional clumps of grass and moss. The values given in Table 6.1 produced the results presented here.

A survey of the literature indicated that a reasonable value for surface storage was 10 mm (Horton, 1938).

Table 6.1 Input parameters for subwatershed J used for the May 10, 1996 test storm.

Landcover	Vegetated	Bare Rock	Stream
Infiltration (mm/hr)	4.0	2.7×10^{-8}	0.01
Manning's n	0.35	0.25	0.02

6.3.3 Time to Peak Discharge

The simulated hydrograph approximates the timing of the observed hydrograph reasonably well (Figure 6.3). The first two sharp peaks of the observed discharge are captured by the simulation, but they are computed to occur 2.5 hours later than the actual peaks. Surface storage is the main control over the start of runoff in the simulation (Figure 6.1). Runoff begins once surface storage is satisfied, computed to occur at 5:40 pm on May 10, 1996, 8.2 hours into the storm event. The offset between the simulated curve and the observed hydrograph suggests that the estimated storage value is slightly high. Reducing the surface storage should minimize the offset. It will also significantly increase the stormwater available for overland flow and infiltration, since only 0.8 mm was left after surface storage was accounted for (Figure 6.1). Changes in the surface storage value could easily double the rainfall available for the model.

Figure 6.3 The observed and simulated (5e7) runoff hydrographs for the test storm. Time zero is 9.30 a.m. on May 10, 1996.

6.3.4 Shape of the Simulated vs Observed Hydrograph

To facilitate a comparison of the shape of the two hydrographs, the observed curve was shifted to match the timing of the first, smaller peak (Figure 6.4). This also emphasizes how well the timing between the first and second peaks matches

Figure 6.4 The observed and simulated (5e7) runoff hydrographs for the test storm on May 10, 1996. Time zero is the beginning of the simulation. The observed hydrograph is shifted 2.5 hours to match the arrival time for the first peak. Values on the graph indicate total discharge for the respective curve.

in the observed and simulated hydrographs. The computed hydrograph approximates the rising limb of the observed hydrograph well, and roughly captures the shape of the first and second sharp peaks. The second peak is slightly overshoot by the computed curve. Further attempts at calibration with respect to infiltration and roughness coefficients are expected to reduce the height of the computed peak. After rising sharply, the computed curve then turns and descends exponentially. In contrast, after a slight dip, the observed hydrograph continues to rise slightly, then declines at a more gentle slope. Runof97 only models overland flow. Any water that infiltrates the ground is removed from the computed system and cannot add to the runoff hydrograph. Therefore the first and second sharp peaks of the observed hydrograph are interpreted to represent surface runoff. Presumably the third more gentle peak is derived from subsurface flow which Runof97 does not simulate.

Subwatershed J mainly comprises exposed quartzite bedrock, with relatively thin lenses of soil (≈ 50 cm) remaining only in small valleys and along stream beds. There is essentially no long-term continuous groundwater flow. This is known because after a rainfall, the streams in subwatershed J dry up totally within a couple of days, and remain dry between rainfall events (Figure 6.5). This is true even in early spring directly after snowmelt, and leads to the conclusion that there is no local groundwater to recharge the streams. Rain water that is infiltrated in the vegetated areas is not driven downwards to replenish groundwater. Instead, if the soil reaches a reasonable saturation level, it travels downslope as interflow and either discharges directly, or displaces downslope water into the streams. Subsurface flow travels more slowly than overland flow, and hence would arrive

Figure 6.5 Long term discharge record for subwatershed J for 1996.

later and taper off more slowly than overland flow. The test storm occurred shortly after snowmelt. Therefore the soil is assumed to have had a relatively high moisture content prior to the rain. This combined with the thin soil layer makes it probable that interflow would be generated even from a very small rain event such as the test storm. Nevertheless, there is no independent evidence to verify this interpretation.

The total computed discharge is 12.2 m^3 , while the observed total discharge is 23.4 m^3 (Figure 6.4). The watershed is roughly 50% bare rock and 50% vegetated, and on the vegetated areas, the modeled infiltration rate exceeded the rainfall rate, so that all rain that fell on vegetated areas soaked in. In this situation, it could be expected that about half the total observed discharge would be contributed by interflow, and the other half by overland flow off the bare rock areas. This is roughly what Runof97 computes, though one should be cautious in interpreting this information because not all overland flow from rock areas will make it into the streams since some will flow across vegetated areas where it will infiltrate and join the interflow.

Based on the relatively good fit of the computed curve to the rising limb of the observed hydrograph, and the seemingly sensible discharge volumes predicted, it is concluded that the model can successfully compute surface runoff. However, these are very preliminary results, and certainly the model requires further calibration and testing. The test storm was in fact a very small event, and thus storage and infiltration consumed a proportionally large amount of the rain. In hindsight, the storm was not ideal for calibrating/testing a surface runoff model. However, it was the only storm for which local rainfall data were available. Subsequent work should involve simulating a heavier rainfall event,

where runoff is expected to play a more dominant role, to more rigorously test the ability of the model to compute overland flow. Additional testing is also required to demonstrate whether the model can perform well for storms that are not also used to calibrate the model.

6.3.5 Distributed Surface Runoff in GIS Format

As stated earlier, the goal of the model is to study distributed surface water processes. In essence, the hydrograph is used mainly to verify that the model is working and to judge the level of confidence appropriate for the resulting surface water maps. Two examples of surface water maps are shown in Figure 6.6. Early in the runoff (Figure 6.6a) streamlines begin to form and water begins to build up and move down the streams. In many places, non-channelized flow occurs. Figure 6.6b shows water depths later in the storm by which time most water has drained, with significant quantities left only in the lower section of the main stream, and the land is relatively dry.

Runof97 can produce as many surface water maps, for any stage of a storm, as the user chooses. Although this has not yet been done, one purpose for these maps is to select from them the maximum water depth that occurs for each cell during the storm. The maximum water depth map can then be converted into a maximum velocity map, producing a map of erosion potential. Such a map will contribute to a better understanding of erosion, and how lime of different sizes is redistributed over the landscape due to storm events. An early conclusion that can be drawn from these first few runs of Runof97 is that in small storms, lime will remain immobile on vegetated surfaces where the rainfall rate is less than the infiltration rate, but for this same rainfall rate, lime may be mobilized on bare rock, or even completely washed off the rock areas into the streams or adjacent vegetation.

A major purpose of Runof97 is to explore how the distribution and connectedness of bare rock areas affects water velocities and erosion. In subwatershed J, it may be possible to plant bands of vegetation that intercept overland flow, reducing downstream water depths and velocities, and delaying the arrival of water by increasing roughness and, in the long term once soil has built up, transferring overland flow to interflow. It should be possible to assess the size of storms that would overwhelm the interception effects of vegetation, and assess the erosive force such storms would exert on the vegetation itself. In particular, Runof97 can be used to identify the optimum places to plant, to gain the greatest reduction in velocities with the least chance of washing out the vegetation.

Another use for the maps is to animate runoff by dynamic display of the maps, hence making a movie picture of surface water flowing over the land. Although this is mostly a *gee-whiz* effect, it does serve a real purpose in education

Figure 6.6 Surface water depth map for subwatershed J, (a) 6 hours into the simulation, and (b) 40 hours into the simulation. Darker values represent greater depths. Vegetated areas have several water depths (light tones), because almost all rainfall infiltrates the ground. Streams accumulate water and are dark by 6 hours into the storm; after 40 hours, some headwater streams are dry (white).

and communication. It becomes visually obvious how different parts of a watershed contribute to runoff and instream flow, and peak flows can be seen to build up and travel downstream to the outlet, combining with flows from other side streams. Where this may be most effective is in combination with the ability of GIS to explore different scenarios, such as the effects of reforestation or the reduction in impervious areas.

During the inspection of the surface water maps (Figure 6.6), it became apparent that they also serve the purpose of checking the hydrologic soundness of the DEM from which the slope and flow direction maps are made. In an early run, flow in the stream in the western section of the subwatershed appeared to divert into the stream just north of it. This was corrected by manually changing the flow direction values so that the correct streamline was defined through this rather flat area. Also, the stepped nature of the current DEM is visible as contour-like lines (Figure 6.6) caused by water building up on the flat tops of the steps. Finally a rim of darker values, indicating greater water depths, is visible along the northwest and northeast edge of the watershed (Figure 6.6b). These cells are collecting water that is running out of the watershed rather than within it, indicating that the watershed boundaries are not completely compatible with the DEM. Many of these problems could be corrected by rebuilding the DEM, this particular DEM having undergone a series of transformations that degraded its quality. Nevertheless the problems seen in this DEM are not uncommon and indicate that a tool like Runof97 may have significant value beyond runoff modeling alone.

6.4 Conclusions

The purpose of Runof97 is to model overland flow rather than stream discharge. However, the only way to test the model is to compare the simulated stream hydrograph at the watershed outlet to actual hydrographic records for the same location. Since Runof97 does not include interflow (all infiltrated water is simply removed from the model system), the simulated and actual hydrographs will diverge depending on the actual amount of water coming from non-surface sources. Preliminary results from Runof97 indicate that the model is performing well for overland flow simulations. The model was calibrated against a small spring rainstorm by adjusting the roughness coefficients for bare rock and streams. Resulting roughness values are reasonable for the type of cover present. The simulated hydrograph described the first two sharp peaks of the observed hydrograph reasonably well, matching the timing between peaks closely and approximating peak flows, although the peaks themselves were delayed in the simulation due to the choice of storage depth. Simulated discharge volumes seemed reasonable, given that about half the rainfall is infiltrated in subwatershed

J and hence should not be included in the simulation. The third broad peak in the observed hydrograph was not simulated. This peak is probably due to interflow, which Runof97 does not include, though this needs to be verified.

Runof97 can produce a series of water depth maps at intervals during a storm. These maps can be used to produce overland-flow maximum velocity maps which can in turn be used to assess erosion potential, and plan revegetation in this industrially damaged watershed. The maps can also be made into movies, thus providing a dynamic visualization of overland flow throughout a storm, an option which may be valuable for education or communication about the effects of different restoration scenarios. In addition, the maps have shown that Runof97 is a valuable tool to assess the hydrologic soundness of a DEM.

Runof97 is still under development and the results presented here are from the first few runs of the model. The model needs to be better calibrated and more rigorously tested, in particular with storms not used to calibrate the model. Thereafter, there are a number of features of the model whose effect should be assessed, such as splitting flows to develop diffuse flowpaths, correcting for topographic pathlength, and the effects of cell size.

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