Modelling the spatial variability of hydrological processes using GIS

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Abstract TAPES-G, a grid-based method of terrain analysis, SRAD, an approximate method of computing daily global short wave, net long wave and net radiation and extrapolating minimum, maximum and average temperature across a landscape, WET, an approximate method of computing spatially distributed soil water content and evaporation and catchment runoff and EROS, an approximate method for predicting erosion potential, are simple terrain-based models for analysing spatially distributed land surface processes. These models operate in a UNIX environment with X-Windows, have full graphics display facilities, and exhibit many of the features of a GIS. The spatial variability of the radiation, thermal, soil water, evaporation and erosion regimes on the 27 km² Lockyersleigh catchment in southeastern Australia is explored using these models.

INTRODUCTION

Models that include the key factors determining system behaviour, but which are based on simplified representations of the underlying physics of the processes, are effective tools for examining spatially variable hydrological processes using GISs. With this approach some physical sophistication is sacrificed to allow improved estimates of spatial patterns in the landscape. These models provide a means of relating "pattern to process" and can operate with "minimum data sets" - adequate spatially distributed data being a major constraint on the application of more sophisticated modelling strategies and GISs. TAPES (Terrain Analysis Programs for the Environmental Sciences) is a suite of integrated FORTRAN77 and C programs that have been developed at the Centre for Resource and Environmental Studies based on this philosophy. This paper describes and demonstrates the utility of some of the TAPES programs.

The TAPES programs have been specifically designed to analyse spatially distributed hydrological, geomorphological and ecological processes in topographically complex landscapes. They have been developed with full graphics interfaces using the UNIX operating system and X-Windows for displaying the results. In addition a number of tools have been developed for statistically analysing and fitting frequency distributions to the results. The TAPES programs are divided into three broad classes that correspond to the principal ways of structuring networks of elevation data: (a) Triangulated
Irregular Networks (TINs); (b) grid-based networks; and (c) contour-based networks (Moore et al., 1991). Because remote sensing and many GIS systems are based on pixel or cellular structures, grid-based methods of analysis are particularly attractive for use in analysing spatially distributed environmental processes. Therefore, only the grid-based TAPES programs are described here.

**TERRAIN ANALYSIS**

TAPES-G is a grid-based method of terrain analysis that calculates slope, aspect, principal drainage direction, specific catchment area, profile and plan curvature and flow path length at each node in a grid-DEM. These attributes are useful in characterizing a wide range of hydrological, erosional and geomorphological processes occurring in complex landscapes (Moore et al., 1991). The algorithm creates a depressionless DEM using the method of Jenson & Domingue (1988) if desired. Specific catchment areas are estimated using either the classical D8 algorithm, that allows drainage from one node to only one of eight nearest neighbours based on the direction of steepest descent, the quasi-random Rh8 algorithm, or the FRho8 algorithm that permits drainage from a node to multiple nearest neighbours on a slope weighted basis. The Rh8 algorithm produces more realistic flow networks than does the D8 algorithm, and the FRho8 algorithm permits modelling of flow dispersion in upland areas, which is important in convex topography (Moore et al., 1992a). TAPES-G can also delineate sub-catchments draining to specified seed-cells (i.e., cells at the catchment outlets).

The first and second derivatives of the elevation surface in the x and y directions (\( f_x, f_y, f_{xx}, f_{yy}, f_{xy} \)) are estimated by applying a second-order, central finite-difference scheme centred on the interior node of a moving 3 x 3 square grid that is passed over the DEM. Forward and backward difference schemes are used to handle nodes on the edges of the DEM (Moore et al., 1992b). Attributes such as slope, aspect and plan and profile curvature can be calculated directly from these first and second derivatives.

**ENERGY AND THERMAL REGIMES**

The surface radiation budget is a driving force for evaporation and photosynthesis processes occurring at the land surface and is highly dependent on topography. Vegetation diversity and biomass production have been shown to be related to radiation and temperature in many studies. Here, we develop an algorithm, SRAD (Moore et al., 1993), for calculating net radiation and its components in topographically heterogeneous terrain. The algorithm also spatially extrapolates maximum, minimum and average temperature.
Radiation

The component terms of the net radiative flux density, $R_n$, include the direct, diffuse and reflected shortwave irradiance (the sum of which is the global shortwave irradiance) and the incoming or atmospheric longwave irradiance and the outgoing surface longwave irradiance (which make up the net longwave irradiance). The input parameters of SRAD include spatially invariant variables such as albedo, emissivity, sunshine fraction, and clear sky transmittance, as well as maximum and minimum temperatures (see below). The shortwave irradiance components are calculated based on Fleming's (1987) CLOUDY algorithm modified to account for the effects of shading from direct sunlight by surrounding terrain at enclaved sites using an improved version of the Dozier et al. (1981) solution.

Temperature

The spatial distribution of minimum, maximum and average air temperature is extrapolated from measurements made at a base-station using a modification of the simple approach proposed by Running et al. (1987). The method corrects for elevation via a lapse rate, slope-aspect via the ratio of short wave radiation on a sloping surface to that on an unobstructed horizontal surface, $S$, and vegetative effects via a leaf area index, $LAI$. In the southern hemisphere this approach increases temperatures on north facing slopes and decreases temperature on south facing slopes relative to a flat surface. This effect is greatest on poorly vegetated slopes (low leaf area index) and negligible in closed forests (high leaf area index). No leaf area index/radiation corrections are applied to estimates of minimum temperature as these occur during the night.

SOIL WATER CONTENT AND EVAPORATION

In complex terrain soil water distribution is controlled by vertical and horizontal water divergence and convergence, infiltration recharge and evaporation. The latter two terms are affected by solar insolation and vegetation canopy, and vary strongly with exposure. The divergence/convergence and solar insolation are dependent on hillslope position. Beven & Kirkby (1979) and O'Loughlin (1986) independently derived wetness indices for characterizing the spatial distribution and size of zones of saturation or variable source areas of runoff generation in a landscape. These indices have been used to model the distribution of soil water content (Moore et al., 1988). These wetness indices are derived from simple catchment drainage theory, and in their simplest form can be expressed in terms of terrain attributes and soil hydraulic properties as:
\begin{equation}
\chi_i = \ln \left( \frac{T_c}{b \cdot T \cdot \tan \beta} \right) - \ln \left( \frac{A_s}{b \cdot T \cdot \tan \beta} \right) + \ln [T_c] - \ln [T_i]
\end{equation}

where \(\chi\) is the wetness index, \(dA_i\) is the element area (m²), \(b_i\) is the outflow width (m), \(\beta_i\) is the slope angle (degrees) and \(T_i\) is the transmissivity (m² day⁻¹) in the \(i\)th element, \(A_s\) is the specific catchment area (catchment area draining across a unit width of contour: m² m⁻¹) and \(\ln(T_c)\) is the areal average value of \(\ln(T_i)\). The integral term represents the upslope area draining across a contour segment of width \(b\) orthogonal to the flow. In equation (1) \(A_s\) is a measure of the steady-state subsurface drainage flux \((q=\text{f} A_s)\), where \(f\) is the net recharge rate: mm day⁻¹), but assumes uniform infiltration over the entire catchment.

Equation (1) has been extended to allow estimation of the spatial distribution of the long-term (i.e., annual average) soil water content and evaporation using an equilibrium approach (Moore et al., 1993). Equation 1 can be rewritten as:

\begin{equation}
\chi_i = \ln \left( \frac{1}{b \cdot \tan \beta} \right) \int \mu dA_i + \ln [P] + \ln [T_c] - \ln [T_i]
\end{equation}

where \(P\) is the precipitation and \(\mu\) is an area weighting coefficient that is dependent on the evaporation, deep drainage and precipitation in each element. This weighting coefficient can be written as:

\begin{equation}
\mu_i = 1 - \left( \frac{E+D}{P} \right), \text{ where } E = E_p \left[ 1 - \left( 1 - \theta \right)^{C/E_p} \right] \text{ and } \theta = \frac{\chi_i}{\chi_{cr}}
\end{equation}

where \(\theta\) is the relative available soil water content \((1=\text{field capacity}, 0=\text{wilting point})\), \(D\) is the deep seepage, \(E\) is the actual evaporation, \(E_p\) is the evaporative demand, \(C\) is a constant and \(\chi_{cr}\) is the critical wetness index at field capacity. The deep seepage, \(D\), can be expressed as the product of the subsoil saturated hydraulic conductivity and a power function of \(\theta\).

The evaporative demand is estimated from the Priestley & Taylor (1972) equation for well watered vegetation under conditions of minimal advection:

\begin{equation}
E_p = \frac{\alpha_e R_n}{\rho \lambda \left( 1 + \frac{\gamma}{\Delta} \right)}
\end{equation}

where \(\alpha_e\) is an empirical constant (=1.26), \(\Delta\) is the slope of the saturation specific humidity-temperature curve and \(\gamma\) is the psychometric constant (functions of air temperature and pressure), \(\rho\) is the density of water, \(\lambda\) is the latent heat of vapourization, and \(R_n\) is the net radiation estimated by SRAD.

Equations 2-4 are solved iteratively, beginning with the element of highest elevation and finishing with the element of lowest elevation at the catchment outlet. These equations are embodied in program WET.

Because of fluctuating rainfall intensities and the short duration of
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rainfall events compared to the travel time of subsurface throughflow, the subsurface flow regime in a catchment rarely reaches steady-state. Barling (1992) observed that during storm events subsurface flow is only affected by a small proportion of the contributing area directly upslope. He modified equation (1) by calculating an effective specific catchment area, $A_e$, using it instead of $A_c$. The method is based on the subsurface flow travel time-specific area curve, $a_e(t)$, where $a_e(t_e)=A_e$ and $t_e$ is the time to equilibrium, proposed by Udny (1984). By specifying different drainage times, which might be the time since the last precipitation event, different values of $A_e$ will be obtained. Program DYNWET performs these calculations using the terrain attributes calculated by TAPES-G as the primary input data. Using relationships similar to equations (3) and (4) and net radiation computed by SRAD, it is then possible to estimate spatially distributed daily soil water content and evaporation.

EROSION POTENTIAL

Moore & Wilson (1992) derived a dimensionless index of the sediment transport capacity of overland flow. They showed that this index was equivalent to the length-slope factor in RUSLE, the Revised Universal Soil Loss Equation (Renard et al., 1991), for a two-dimensional hillslope. This index can be easily extended to three-dimensional terrain to map the effect of hydrology, and hence topography on soil erosion. The erosion potential is a power function of specific catchment area (catchment area per unit width) and the sine of the slope angle. The exponents on these two terms range from 0.4 to 0.6 and 1.2 to 1.3, respectively.

STUDY SITE

The 27 km² Lockyersleigh catchment is located in the Goulburn-Marulan region of the Southern Tablelands of New South Wales, Australia (34°41'S, 149°56'E). Elevations range from 600-762 m and the terrain is undulating and largely cleared. The vegetation is a mixture of native and introduced grasses with open woodlands on the higher ground in the east and southeast. Tussock grasses occur in most creek depressions and native sedges are widespread, indicating impeded drainage. Soils are duplex with bleached sandy/silty A-horizons, changing abruptly to a yellow heavy clay B-horizon (Kalma et al., 1987).

Intensive field experiments, including soil water measurements, ground-based measurements of energy fluxes at four sites and tethered balloon and airsonde measurements of the boundary layer (temperature, humidity and wind speed) were carried out in February-March 1992.
RESULTS AND DISCUSSION

A 30 x 30 m digital elevation model (DEM) was developed for the catchment by line digitizing 10 m contour interval contour lines, streamlines, and spot

![Diagram](image)

**Fig. 1** (a) Shaded relief diagram of the study area, and predicted distributions of: (b) slope (%) within the Lockyersleigh catchment, (c) annual net radiation (W m⁻²), and (d) erosion potential.
heights from a 1: 25 000 scale topographic map and then fitting an interpolating surface using ANUDEM (Hutchinson, 1989). ANUDEM is a finite difference interpolation method with a drainage enforcement algorithm that ensures fidelity with the drainage network and eliminates anomalous pits or sinks in the DEM. This DEM formed the primary data for the subsequent analysis.

A shaded relief diagram (x 5 vertical exaggeration) of the region, derived from the 30 x 30 m DEM using SHADEDEM, is presented in Fig. 1a. The

![Fig. 2 (a) Predicted evaporation (mm day⁻¹) and (b) soil water content (m³ m⁻³) on 2 March 1992; (c) comparison of measured and predicted evapotranspiration on 2 March 1992 at nine nodes along a 0.54 km transect of the Lockyersleigh catchment.](image)
spatial distribution of slope within the Lockyersleigh catchment computed by TAPES-G is presented in Fig. 1b. Figure 1c presents the spatial distribution of annual net radiation (W m⁻²) calculated by SRAD. The computed global short wave radiation and net radiation on a horizontal surface are in close agreement with measured values (±5% on an annual basis). The spatial distribution of erosion potential is presented in Fig. 1d. Erosion potential is less than 1 and 5 over 51 and 90% of the catchment, respectively, and is highest in the steeper areas along the north-eastern perimeter of the catchment, as expected.

Evaporation and soil water content for 2 March 1992, calculated using the quasi-dynamic approach (both based on calculated values of net radiation for 2 March), are presented in Figs 2a and 2b, respectively. The effective evaporation calculated from differences in measured (on 28 February and 3 March) profile soil water contents at nine measurement sites along a 0.54 km transect are compared to predictions using the quasi-dynamic approach, with both the computed and measured soil water contents, in Fig. 2c (see also Guerra et al., 1993). For these calculations we assumed spatially uniform soil properties, but the limited soil textural data indicates that there are differences in soil type over the catchment. These results show reasonable agreement, but suggest that there are potential problems with the spatial resolution of the DEM and the georeferencing of the field sites. Higher resolution DEMs (1:5000 to 1:10 000) appear to be necessary to drive these types of spatially distributed models.

The models and equations presented here are relatively simple but physically-based, are easy to use, and have limited data requirements. With their visualization capabilities, they are effective tools for examining the spatial variability of hydrological processes in real three-dimensional terrain.

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