LAND HYDROLOGY

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Summary

Data are critical to land surface hydrology – spatial analyses and spatial data sets such as those derived by remote sensing are increasingly relevant in aiding the development and application of hydrological models. Geographic Information Systems provide powerful platforms on which typically point hydrological measures can be collated and viewed within a spatial and multivariate framework. The ready availability of digital terrain models enables simple routine delineation of catchment boundaries, drainage networks and flow paths. The incorporation of remotely sensed data into modelling practice presents new opportunities but also new challenges.

Typically, hydrological models have been developed with respect to the availability of data either to parameterize or to calibrate the model. Many variables acquired by remote

sensing are often incommensurate with existing hydrological models. The challenge is to formulate models to incorporate such measures, preferably with the minimum number of parameters. Whilst remote sensing techniques cannot at present answer all data uncertainties in simulating hydrological systems, their potential value, in terms of providing large-scale measures of surface characteristics, land surface thermal responses and surface moisture content, is apparent.

1. Introduction

Hydrology is a fundamental and diverse subject area. Its study has grown from two related pursuits – hydrological science, i.e. the understanding of the physics of water, and hydrological engineering, i.e. the practical management of water resources and threats. As water is fundamental to life on Earth, its abundance and scarcity are key to the development and sustainability of every ecosystem. The understanding of terrestrial hydrology is, therefore, of great importance in providing effective and sustainable management.

The natural environment displays great variability across the entire range of spatial scales, both in terms of land surface characteristics and climatic regimes. Data to define this variability must, therefore, play an integral role in hydrological analyses. Traditionally, field measures of hydrological properties and fluxes have tended to be point measures. Geoinformatics is facilitating a more coherent spatial context to hydrological studies. Geographic Information Systems provide powerful platforms on which hydrological measures can be collated and viewed within a spatial and multivariate framework. Recent advances in remote sensing and data availability are also providing new insights into a number of hydrological problems -- spatial data are increasingly being used to develop and test hydrological models. The incorporation of spatial data is not, however, without complications. In the first section of this chapter, typical hydrological measurements are reviewed. In the following sections, case studies of spatial analyses and the incorporation of spatial data into hydrological models are presented. The final section summarizes the advantages offered by spatial information.

2. Traditional Hydrologic Field Measurement

In very general terms, quantitative hydrology is concerned with the estimation of one or more of the terms within the hydrological water balance, at a range of spatial and temporal scales;

$$Q = R - E - \Delta S \tag{1}$$

where Q is surface discharge, R is rainfall, E is evapotranspiration and ΔS is the change in sub-surface storage. Whilst this equation is an inherently simple mass balance, many practical difficulties arise in the measurement, modelling and prediction of each term. In common, most hydrological measurements are point measures, or at best integrate over a variable and typically unknown domain.

2.1. Discharge

The prediction of surface discharge is critical for a whole range of applications. Catchment discharge provides surface water for abstraction, maintains many surface ecosystems, and periodically brings devastating floods. Catchment discharge is usually estimated through the installation of a gauging device such as a weir or flume. These relate the water level upstream of the device to the discharge through it. As the derivation of the basic form of this relationship is based on idealized fluid mechanics, the coefficients of the relationship for each device must be calibrated either in the laboratory or *in-situ*. Catchment surface discharge represents a catchment-integrated hydrological flux in that the response of the catchment area should drain through one point (or outlet). In practice, hydrological catchments are typically defined according to surface topography, which may or may not correspond to areas where sub-surface controls may dominate fluxes.

2.2. Rainfall

Rainfall might be seen as the starting point of land surface hydrology as all consequent hydrological fluxes are derived from rainfall. Measurement of rainfall has traditionally been achieved by direct sampling of precipitation volumes through the use of raingauges. Whilst a variety of designs of gauge exists, they all represent essentially point measures.

2.3. Evapotranspiration

The understanding of evapotranspiration is required for estimating catchment losses, vegetative growth, crop yields, the partition of rainfall into surface runoff, etc. Evapotranspiration is perhaps the most difficult hydrological flux to measure. Evaporation pans have been devised to provide estimates of potential evaporation. However, they cannot represent vegetative controls on moisture loss. Additionally, the use of pans is complicated by feedbacks with the moisture content of the overlying near-surface atmosphere – if the actual evaporation rate is low, then the atmospheric demand of moisture is high thus elevating pan losses, and *vice versa*. To account for these feedbacks, empirical “pan coefficients” are employed as corrections.

More recently, Bowen ratio and eddy correlation devices have been devised to measure actual evapotranspiration losses. Whilst these represent a significant improvement on the use of pans, they measure fluxes from an area (or fetch) of between 100 –1000 m^3 that varies according to wind direction strength and convective stability of the atmospheric boundary layer. While they provide areally-integrated measures, it is clear that significant variability of evapotranspiration may exist within the area of the fetch. This variability may be especially important in that it will determine the available storage, which given rainfall will determine the occurrence of saturation -- responsible for fast-flowing surface runoff.

2.4. Storage (Sub-surface Flows)

Changes in sub-surface storage and groundwater flows are typically measured through direct observation of water levels or contents. In shallow porous media this is usually achieved through installing piezometers at different locations. In deeper groundwater systems, boreholes are sunk from which the water table can be measured. Networks of boreholes provide hydraulic gradients from which groundwater velocities can be inferred. Hydraulic conductivity is estimated through slug (pulse) tests where water is removed (added) and the rate of recovery to the prior level is observed. This provides a measure of conductivity of the media surrounding the borehole.

3. Spatial Analyses

Geographic Information Systems provide powerful platforms on which typically point hydrological measures can be collated and viewed within a spatial and multivariate framework. This enables rapid generation and analysis of derived spatial fields. For instance, point raingauges can be plotted in relation to the topographic features of a study catchment. Through the use of interpolation techniques such as thin-plate splines or geostatistical methods (see *Stochastic Modelling of Spatio-Temporal Phenomena in Earth Sciences*), a continuous field of rainfall characteristics can be plotted, utilizing the observed relationship between rainfall and topography. As an example, Figure 1 shows the variability of summer rainfall totals as a function of the El Nino and La Nina extremes of the Southern Oscillation (expressed as a ratio) for the Williams River catchment, Australia (1300 km^2). As can be seen, much spatial variability exists across the catchment, with strong topographic effects controlling the effects of the extreme phases.

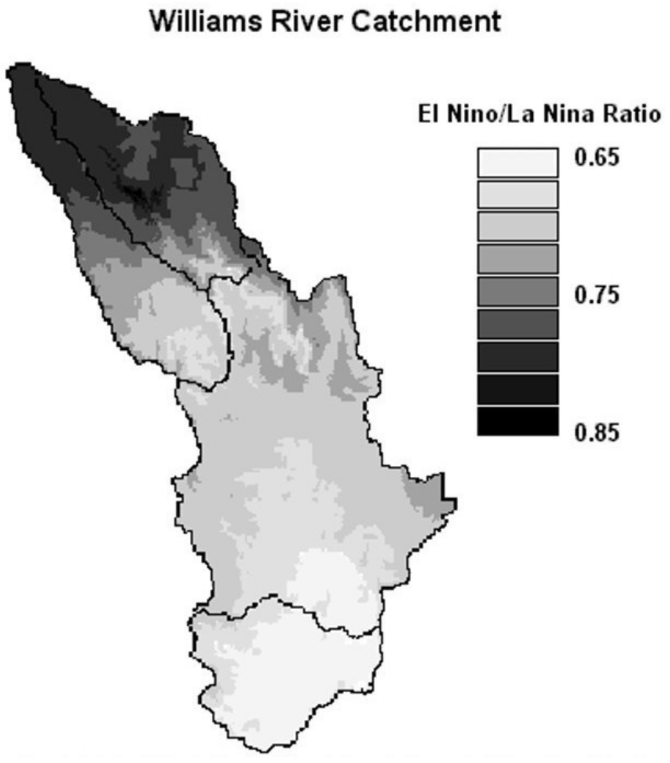

Figure 1: Analysis of El Nino Southern Oscillation effects on rainfall across the Williams River catchment, New South Wales

3.1. Digital Terrain Models (DTM)

Possibly the most important spatial data have been Digital Terrain Models (DTMs, see *Landform and Earth Surface*). DTMs were originally built through the collation of point measures of elevation obtained through traditional manual surveying techniques. The advent of remote sensing devices, such as airborne laser altimetry (LiDAR), has meant that high spatial resolution DTMs can be obtained for almost any study area. The ready availability of digital terrain models enables simple, routine delineation of surface catchment boundaries, drainage networks and flow paths. DTMs have been put to many other uses within hydrology including the estimation of relative moisture content based on topographic controls. Figure 2 shows a DTM for the Little Washita catchment, USA.

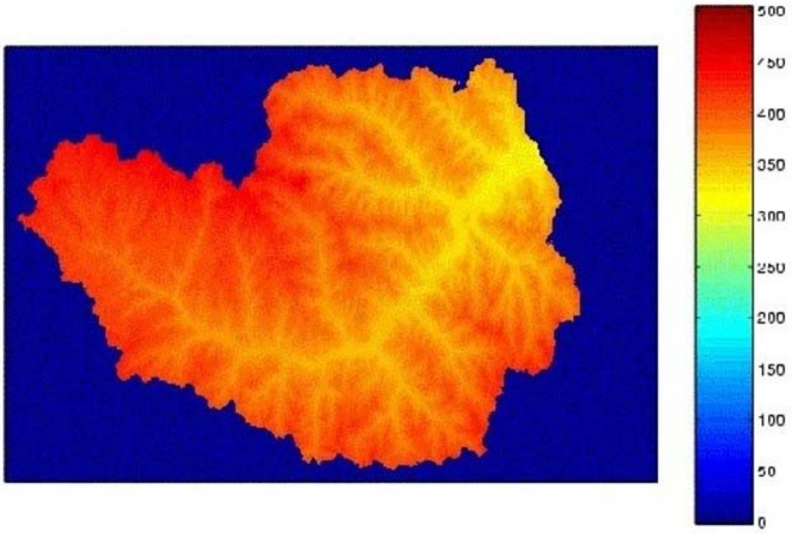

Figure 2: DTM of the Little Washita catchment, USA.

3.2. Groundwater Mapping and Management

Good groundwater management is increasingly important -- many aquifers are vulnerable to sea-water intrusion if the water tables are lowered sufficiently (i.e., through over-extraction). Alternatively, increased industrial, agricultural and waste management practices threaten aquifer water quality. Point sources of pollution produce growing plumes as they travel through the aquifer. It is, therefore, clear that managing groundwater resources, and the associated threats to them, requires well-developed spatial analyses.

Spatial digital groundwater models have been developed since the 1970s, their increasing sophistication limited only by computational constraints. Advanced packages such as Visual MODFLOW provide 3D aquifer modelling with powerful user interfaces. Such models rely on borehole and aquifer characteristics data, usually collated through a GIS. GIS also provides a powerful platform for the management of surface activities that might impinge upon the aquifer.

Figure 3 shows part of the Tomago Sandbeds, located in New South Wales, Australia.

This aquifer forms part of the Hunter Water Corporation potable supply network for the Newcastle region. The aquifer also supports an extensive coastal wetlands system which is protected as a wildlife reserve (indicated by cross-hatched area). Additionally, Tomago is also mined in specific locations for sand and gravel with the potential for adverse impacts on water quality. It should be apparent that, for managing the competing demands of industrial activities and the supply of potable water whilst maintaining wetland water levels, the geoinformatic system used to derive Figure 3 provides an invaluable tool.

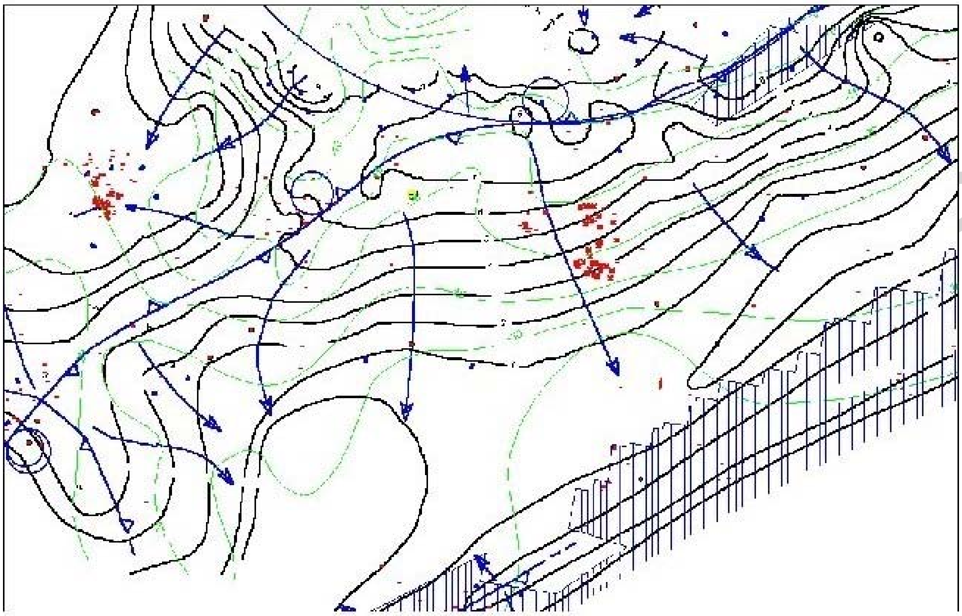

Figure 3: Output from a Groundwater Geographic Information system. Varying water table levels and flow direction are shown.

4. Geoinformatics and Hydrological Modelling

The integral role of hydrological processes in the natural environment has lead to the development of hydrological models to simulate the components of the terrestrial water balance. One substantial complication in the application of hydrological principles and laws to practical hydrological problems is the complexity of the natural environment. For example, rarely, if ever, would a natural hillslope exhibit the homogeneity of the laboratory soil cores on which hydrological laws governing water flow were established. One could argue that, if sufficient data were available to characterize the natural variability of the hillslope, then hydrological "physics" could be applied. However, the typical scarcity of relevant hydrological data means that such insights do not exist at the scale of variability.

The problems of natural variability and data scarcity have meant that the development of a single hydrological model based upon on a fundamental "physics" of hydrology is unattainable. As a consequence, hydrological models are largely "conceptual", in that they are constituted by simplified representations of the mechanisms perceived to dominate the hydrological problem at hand. This means that there exists a whole range of different hydrological models to achieve specific tasks at specific spatial and temporal scales. These models include those describing catchment rainfall-runoff, groundwater movement and recharge, and land-atmosphere interactions, amongst many others.

In the application of any given model to a hydrological problem, data play a central role in the parameterization, calibration and testing (or validation) of the model. Model parameterization can be thought of as the attribution of specific model parameter values through measurement. Calibration is the process of adjusting model parameters to increase the agreement of simulated to measured hydrological fluxes (e.g. discharge, evapotranspiration), whilst model testing is the process of comparing the predicted fluxes of a calibrated model against a further measured set of hydrological fluxes.

In recent years, more spatial information has been available for hydrological studies. In particular, remote sensing offers many new opportunities in providing additional data with which to parameterize and calibrate models. The incorporation of spatial information, in terms of either distributed ground-based measurements or remotely-sensed imagery, within hydrological methods and models is not always straightforward. For example, measured data are not often commensurate with the conceptual model structure in the sense that the observation can be directly inserted into the model – often the model structure itself must be adapted to provide variables commensurate with the observations.

Other problems exist with the incorporation of remote sensing data – such data often require an interpretative model to provide the “observed” variable of interest. For instance, a thermal sensor records longwave emissions as a “data number” (0-255). These data subsequently require a model of atmospheric attenuation to provide a surface temperature. The requirement of an interpretative model induces a significant degree of uncertainty in the “observation”.

In the following sections, case studies are presented where spatial data have been incorporated into hydrological modelling.

4.1. Distributed Hydrological Catchment Modelling

Perhaps the most ubiquitous of hydrological models is the rainfall-runoff model which simulates water balance dynamics at the catchment scale. Because of the significance of water in terrestrial ecosystems, catchment models are an integral part of virtually all environmental models formulated at the catchment scale. Their applications range from catchment water and nutrient balances, at a range of temporal scales, to biophysical models.

One hydrological model that exploits spatial terrain information is TOPMODEL. The model utilizes a concept of hydrological similarity to simulate the response of different parts of the catchment. An index of similarity, the “topographic index”, is calculated for each DTM pixel of the catchment as;

$$TI_{x,y} = \frac{A_{x,y}}{\tan \beta_{x,y}} \tag{2}$$

where TI is the topographic index, A is the upslope area flowing through pixel x,y, and $\tan \beta$ is the slope of the pixel. Figure 4 shows the resultant topographic index values for the Little Washita catchment. Each class of TI is assumed to be hydrologically similar and hence pixels within each individual class are assumed to exhibit the same propensity to saturate. The TI distribution can therefore be used to estimate the dynamics of variable saturated areas as the catchment wetness increases during a storm. As can be seen from figure 4, steep mid slopes exhibit relatively low TI values, whilst lesser sloping valley bottoms exhibit higher TI values indicating a higher propensity to saturate.

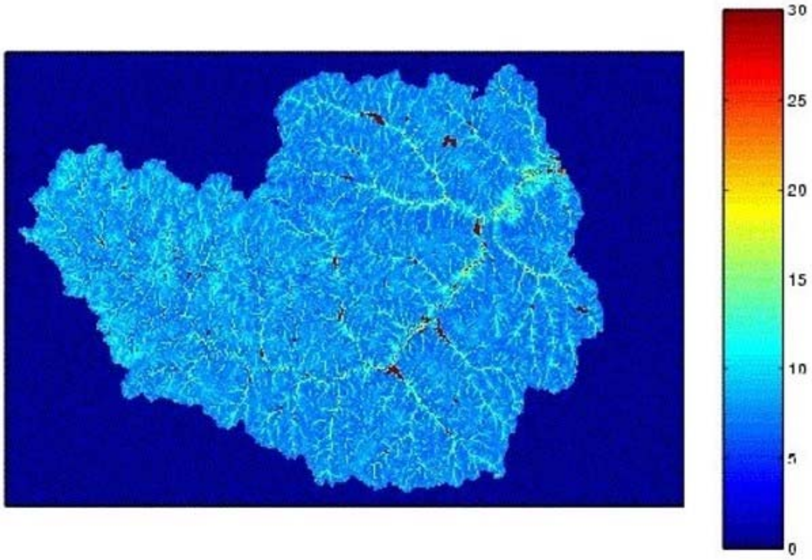

Figure 4: Topographic index calculated for the Little Washita catchment, USA.

An additional advantage of the TOPMODEL approach is that the map of TI classes can be used to project catchment responses into space. This may be useful in a number of contexts. For example, the identification of likely saturation-prone areas may aid in the delimitation of nitrate buffer zones. Additionally, the ability to provide spatial simulations of moisture content/water levels through the use of the topographic index provides additional opportunity to test model simulations against piezometer/borehole level point measures (i.e. calibration or validation).

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Biographical Sketch

Stewart Franks lectures in Environmental Engineering at the University of Newcastle, Australia. His research interests include environmental modelling and uncertainty estimation.