Use of Catchment Attributes to Identify the Scale and Values of Distributed Parameters in Surface and Sub-surface Conceptual Hydrology Models

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Abstract: Improved prediction for problems in catchment hydrology requires an ability to spatially disaggregate and connect surface and sub-surface components. This paper considers two hydrological models for use in such disaggregation and coupling: a lumped conceptual rainfall-runoff model (IHACRES) and a physics based conceptual groundwater discharge model. Smaller gauged catchments in the vicinity can be used to regionalise and parameterise the coupled model using catchment attributes prior to running the model in a larger catchment with fewer gauges. Regionalisation in gauged catchments at appropriate scales would capture the uncertainty of the relationships between catchment attributes and model parameter values, including the upper and lower boundary of parameter values. In an ungauged and disaggregated catchment, its landscape attributes would be inserted into the regional relationships to provide the parameter bounds for constraining the proposed coupled model. The aim of this catchment disaggregation is to be able to improve on previous catchment or sub-catchment recharge-discharge models, so that modelling can be carried out at the management scale.

Keywords: Rainfall-runoff models; Groundwater discharge; Regionalisation; Scale.

1. INTRODUCTION

Effective hydrological modelling of watersheds is an essential tool in the management of land degradation and its off-site impacts, such as those associated with salinity and nutrient problems. Various methods have been used in the past to model processes and responses in catchment hydrology. Catchment hydrology models can be considered crudely as either physical, conceptual or empirical. Each of these modelling approaches suffer from certain inadequacies [Wheater et al., 1993].

Many hydrological modelling studies have achieved excellent correlation between the modelled and observed streamflow, especially during the calibration period [Post and Jakeman, 1996; Chiew and McMahon, 1994]. This correlation is often reduced during subsequent simulation periods with little or no correlation occurring in some catchments. Beven [1997] states that model calibration should immediately imply uncertainty. Often this uncertainty is most likely due to the failure to take the spatial distribution of input variables or parameters into account and/or poor representation of the hydrological processes being modelled. In many cases model parameters have been successful in obtaining a good fit to the observed response even when the physical process underlying the model is questionable.

The complexity of the environment and data collection restraints have seen many researchers favour lumped conceptual models. This is because most models, especially distributed ones, are over parameterised with respect to the information required to calibrate them. If however distribution takes place at the largest possible scale less information is required for parameter estimation. For instance surface hydrology such as infiltration and recharge needs to be modelled at the management scale, whereas routing can be carried out at the sub-catchment or catchment scale. Similarly subsurface discharge needs to be proportioned at the land management scale, but routed at the subcatchment or hydrogeomorphic unit (HGU) scale (See section 5.3).

This paper considers two hydrological models: IHACRES a lumped conceptual rainfall-runoff model [Jakeman and Hornberger, 1993] and a physics based conceptual groundwater discharge model developed by Sloan [2000]. The IHACRES and Sloan [2000] models have been used to model the surface and subsurface hydrological response of a catchment [Croke et al., 2001]. Two possible avenues of improvement are argued here. Firstly by using the appropriate catchment attributes it may be possible to parameterise the IHACRES model in a way that better represents the hydrological response. This would in turn allow model simulations of stream flow to be carried out on ungauged catchments. This has been attempted previously by Post and Jakeman [1996, 1999] and Kokkonen et al. [2002] with some success. In the case of the Sloan model, catchment attributes such as transmissivity, porosity and hill slope length are already used to estimate discharge. Secondly improvements may be made by adjusting the scale at which both conceptual models are lumped to determine the most appropriate division of sub-catchments for model accuracy.

2. STREAMFLOW MODELLING USING IHACRES

The IHACRES model is a lumped conceptual model which attempts to simulate the rainfall-runoff response of catchments as total streamflow. It uses temperature and rainfall data to estimate streamflow, with parameters calibrated prior to simulation by comparison with observed streamflow data [Jakeman and Hornberger, 1993]. The model has been shown to be very effective in modelling total streamflow and separating this flow into its slow flow (base flow) and quick flow components in a range of catchments [Jakeman and Hornberger, 1993; Littlewood and Post, 1995; Post and Jakeman, 1996; Post and Jakeman, 1999; Chapman, 2001; Dye and Croke, 2001].

The IHACRES model consists of two modules, a non-linear loss module to convert rainfall to effective rainfall, and a linear module to convert effective rainfall to streamflow [Jakeman and Hornberger, 1993]. Various forms of the non-linear loss module have been devised [Jakeman et al., 1990; Evans and Jakeman 1998; Croke and Jakeman, 2002], although all use temperature and rainfall to estimate a relative catchment moisture store index. This in turn determines the proportion of rainfall that becomes effective rainfall. A linear module is then used to route effective rainfall to streamflow using quick and slow flow components.

The IHACRES model has many advantages, one of which is that it does not suffer from substantial over-parameterisation, using only five to seven parameters depending on the version. The model structure in Figure 1 is a simple representation. A more detailed description of the model and the equations used can be found in Jakeman and Littlewood [1990], Jakeman and Hornberger [1993] and Evans and Jakeman [1998].

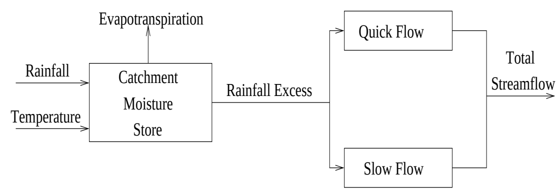

Figure 1: Basic structure of the IHACRES model

3. GROUNDWATER DISCHARGE MODELLING USING THE SLOAN MODEL

The groundwater discharge model developed by Sloan [2000] can be modified for this proposed model coupling so that the model simulates groundwater discharge (baseflow) based on recharge supplied by the IHACRES model and assumes an initial steady state groundwater storage. Sloan [2000] argues that previous groundwater discharge functions depend only on groundwater storage and as a result do not adequately reproduce the actual discharge. Sloan [2000] proposes the use of a new discharge function (dependent on groundwater storage and recharge) which describes the hysteresis between storage and discharge. The model assumes that the movement of water in the saturated region of the river catchment can be adequately described by the Dupuit-Boussinesq equation. In its simplest form the Sloan model is represented by one parameter, which is derived from three physical properties: hillslope length, transmissivity and porosity. See Croke et al. [2002] for more details of this model.

4. REGIONALISATION AND SCALING

Regionalisation of lumped conceptual models implies that the model parameters can be related to catchment attributes at a particular scale or range of scales. Relating catchment attributes to model parameters has already been attempted in the case of the IHACRES model with some success [Post and Jakeman 1996, 1999; Kokkonen et al., 2002; Post and Croke, 2002], although the relationships between model parameters and catchment attributes require further investigation.

Research into scale effects in hydrological processes has been intensive in recent years. Wood et al. [1988] put forward the concept of Representative Elementary Area (REA). REA attempts to identify a spatial scale at which distributed catchment processes remain simple and defined without taking local heterogeneity at that scale into account. Others use statistical similarity, scaling and multiscaling to describe the heterogeneity of catchment attributes [Wood, 1995; Gupta and Dawdy, 1995]. These scale issues revolve around around our ability to estimate catchment processes such as infiltration and overland flow at large spatial and temporal scales. Theories describing these processes have been successful at smaller scales. However given the expense of collecting field data needed to calculate these processes, methods are needed to distribute catchment processes so that this information can be used most effectively at larger scales where measurements may or may not have been taken. Sivapalan and Kalma [1995] point out there is no concensus on scale issues and more research is needed.

Hydrological processes can be different at different scales. It is therefore important to test and perhaps regionalise hydrological models at a number of scales. Our understanding of the heterogeneity of catchment processes and attributes is one limiting factor in applying physical based models. It is for this reason that the concept of Hydrological Response Units put forward by Flugel [1995] is favoured here. HRUs separate a catchment into areas based on common attributes such as soil, slope, vegetation, hillslope length etc. These common areas have been called Hydrological Response Units (HRUs) as it is assumed they share common hydrological response characteristics. Obviously the organization of catchment attributes into HRUs is dependent on the aim of the modelling, scale of prediction, the scale of the original catchment attribute maps and their organization into classes. Recent advances in remote sensing and digital elevation models have allowed mapping of catchment attributes such as vegetation, leaf area index, landuse, soil properties, slope, aspect, hillslope length and contributing area in more detail.

Linking lumped conceptual models spatially can be accomplished by first disaggregating a catchment into a number of smaller sub-catchments. The scale at which catchment properties are important can be tested in a simple way by changing the threshold flow accumulation, determining sub-catchment size and running the model at each scale. For instance one could start with relatively few sub-catchments and with each model run, increase the number of sub-catchments. Using certain performance criteria the most appropriate scale to run the model for each catchment may then be determined. This scale would be when no further improvement in performance, such as correlation between the modelled and observed variables (eg streamflow and electrical conductivity) is seen and when other model properties are most (eg physically) plausible.

5. PROPOSED MODELLING IN THE LITTLE RIVER CATCHMENT

The Little River catchment in northern New South Wales (Figure 2) covering an area of over 2500 km^2 was chosen as the study area. This choice was largely due to: salinity problems present in the catchment; the heterogeneous nature of the catchment in terms of landscape; landuse and climate; the presence of stream gauges in the catchment; and data availability.

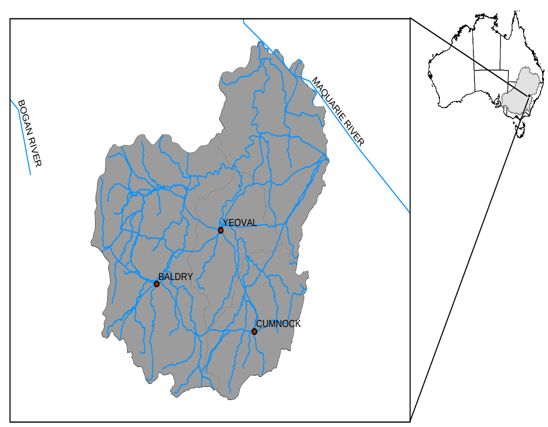

Figure 2: Location of the Little River catchment

5.1 The Model Coupling

The proposed study investigates a range of catchment attributes and their ability to parameterise the coupled IHACRES model. This requires development of the non-linear module of the IHACRES model, including replacing the present use of temperature and catchment moisture deficit to calculate evapotranspiration with actual evapotranspiration estimated from remote sensing and/or other traditional methods. The non-linear module can then output both effective rainfall (now defined as contribution to the quick flow component only) and recharge. The redefined effective rainfall is then passed to the linear module to obtain the quickflow component of streamflow. Recharge is then used to estimate baseflow using the Sloan [2000] model component. This formulation (Figure 3) is described in more detail by Croke et al. [2002].

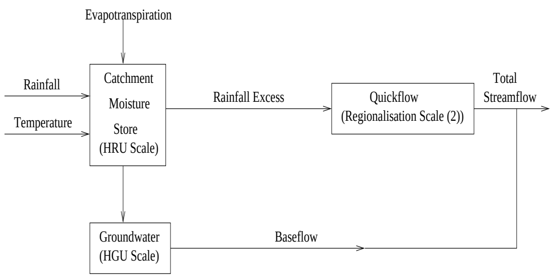

Figure 3: Basic structure of the IHACRES-Sloan recharge-discharge model

5.2 Testing the Scale of Disaggregation

Initially the original IHACRES model (including the linear module) is being calibrated on catchments that have stream gauging stations. This allows a comparison between observed and modelled streamflow during a simulation period and ensures the model broadly reproduces the response of the hydrological processes present in the catchment. The catchment was then disaggregated into smaller catchments using a threshold area for flow accumulation of 45 km^2 from a 25m digital elevation model (Figure 4). The size of the sub-catchments can be decreased with each model run to test the effect of subcatchment scale.

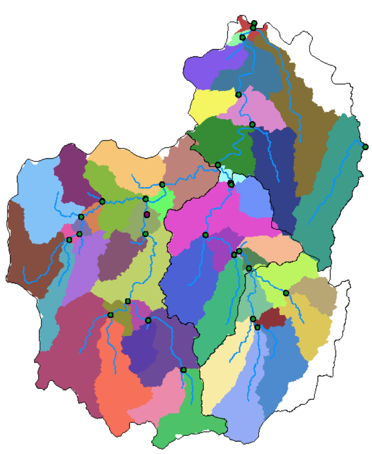

Figure 4: Disagregation of the catchment into sub-catchments

5.3 Use of HRUs, HGUs and Unique Catchment Attribute Combinations

It is proposed that the sub-catchments then be separated into hydrologic response units (HRUs) based on slope class, vegetation and soil combinations. This forms the surface layer of the model. For each unique HRU estimates of catchment attributes such as topographic properties, potential evapotranspiration, saturated hydraulic conductivity, soil water holding capacity and recharge potential can be inferred from data or observable quantities. An attempt can then be made to use these physical properties to parameterise the IHACRES model. From over four thousand combinations of subcatchment number, slope class, landuse and soil class for the Little River sub-catchments shown in Figure 4, 83 unique combinations were identified. Some of these combinations are shown in Table 1. Estimates of catchment attributes would therefore only be carried out at most for these unique soil, slope and vegetation combinations, although simplified combination sets can also be tested.

Table 1: Unique combinations of soil, slope and landuse classes for the Little River catchment (Subset from 83 records)

Frequency	Slopeclass	Landuse	Soil
61	1	Timber	Red Solodic Soils
2	1	Urban	Non-calcic Brown Soils
4	1	Water	Non-calcic Brown Soils
6	2	Cropping	Alluvial Soils
1	2	Cropping	Euchrozems
29	2	Cropping	Non-calcic Brown Soils

The subsurface layer is disaggregated in the form of hydrogeomorphic units (HGUs). Characterisation of HGUs can be largely based on geology mapping in the area and known groundwater systems. As it is still unclear in many hydrogeomorphic studies whether these systems are highly local in nature or whether they cross sub-catchment boundaries, both scenarios will be tested. In the first instance the hydrogeomorphic units (HGUs) are assumed to be local systems not crossing sub-catchment boundaries. This means that the HGU beneath the HRUs receives recharge from each HRU and discharges this recharge at the outlet point for the sub-catchment as baseflow. In the second instance hydrogeomorphic units would be based on known geology and groundwater systems in the catchment and be thought to cross sub-catchment boundaries. Each HRU above a HGU would contribute recharge to the HGU with accumulative discharge occurring at the furthest downstream sub-catchment outlet point containing that HGU. Figure 5 summarises the modelling strategy.

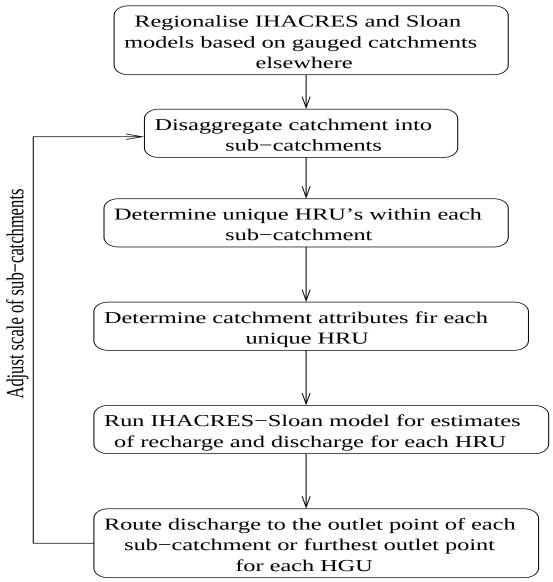

Figure 5: Modelling strategy

Adjustments to the scale of sub-catchments would be made until modelled results for both surface (using the IHACRES model) (recharge) and subsurface (using the Sloan model) (discharge) most closely resemble observed results. However in order to reduce the uncertainty of parameter estimates in the models, constraints must be imposed on their values. Such constraints can be derived from regionalisation results. What is required for this are not only relationships between mean parameter values and landscape/catchment attributes, but also the uncertainty of the relationships. In the simplest case, the regionalisation would yield upper and lower bounds on the parameter values. In an ungauged and disaggregated catchment, its landscape attributes would be inserted into the regional relationships to provide the parameter bounds for constraining the IHACRES and/or Sloan model.

The aim of this catchment disaggregation is to be able to improve on previous catchment or sub-catchment recharge-discharge models, so that modelling can be carried out at the management scale, represented here by hydrologic response units. This is seen as imperative if land managers are to be provided with effective management options. In essence modelling would take place at three scales. The first models at the management scale (Scale 1 in Figure 6) using the physical semi-distributed model regionalised from smaller gauged catchments elsewhere. The second models at the sub-catchment scale (Scale 2 in Figure 6) by routing the flow from each HRU to the sub-catchment outlet point or furthest downstream outlet point containing a HGU. Finally flow is routed to the outlet point closest to a gauging station so modelled results can be compared to observed streamflow. Figure 6 shows these three scales.

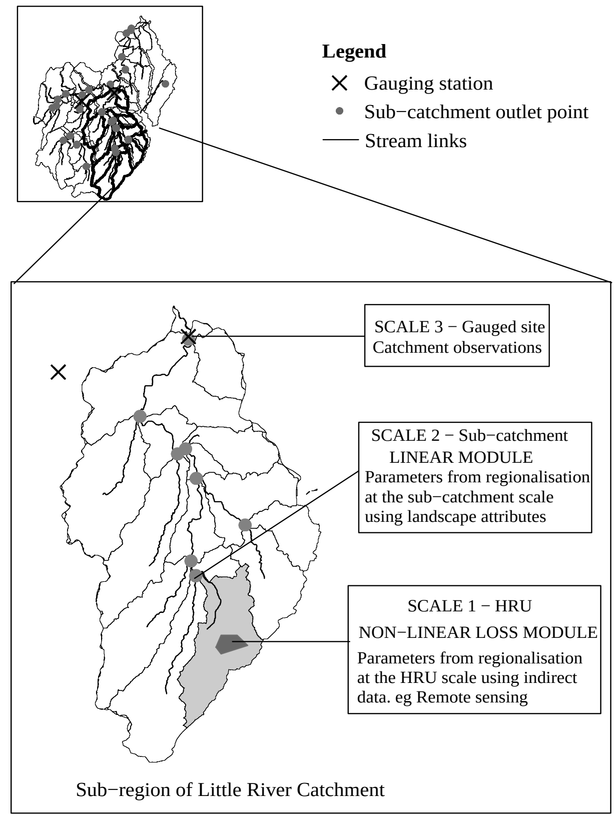

Figure 6: Modelling from management to catchment scale

6. DISCUSSION AND CONCLUSION

If catchment attributes can be used to structure conceptual models to assist in parameterising them over appropriate spatial scales, then our reliance on calibrated parameter values (in the catchment of interest) to produce reasonable modelling results may be reduced. This will in turn lead to greater understanding of the hydrological processes at work. Although using catchment attributes to parameterise conceptual models has had limited success in the past it is still an area worthy of research. If physical attributes can be successfully used to assist in parameterising conceptual models then these models can be applied in areas where observed quantities such as stream flow are absent.

The IHACRES model has been chosen in this case because of the relatively few parameters it needs to calibrate the model and successful application in previous regionalisation studies. It also seems capable of representing the hydrological processes at work in a variety of catchments. The Sloan [2000] model already has a parametrically efficient physical nature, in that it utilizes catchment attributes such as transmissivity, porosity and hillslope length. Future development of the Sloan model will include adjustments for a sloping aquifer.

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