Conceptual and Digital Terrain Modelling of Regolith-Catenary Units for Resource Assessment

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Abstract: This paper outlines a concept that emphasises the geomorphological component to landscape modelling and simulation for soil resource assessment. The conceptual process puts the soil resource into a dynamic 3-dimensional geomorphological landscape and presents information as regolith-terrain data in the context of Regolith-Catenary Units (RCUs) in an explicit and repeatable process. RCUs are 3-dimensional regolith-terrain systems and are viewed as a composite regolith-terrain entity. They are described through soil geomorphic techniques applied to the whole regolith. Observations of the regolith are limited so conceptual models of the regolith-terrain as RCUs are necessary. Spatial expression of RCUs is achieved through the predictive capabilities of digital terrain analysis using derivative functions from digital terrain models (DTMs). Landform attributes are combined as RCU components through a set of 'fuzzy' rules to form simulated RCUs that are more faithful to the conceptual understanding of landforms and geomorphic processes. The concept is applied to predicting regolith attributes in a forested terrain in SE Queensland.

Keywords: Soil-landscape modelling; Terrain analysis; Geomorphology; Hillslope processes

1. INTRODUCTION

An effective understanding of how landscapes are composed and operate is required to develop solutions to an increasing range of environmental problems. Should that understanding need to include the layers of material which extend from the surface to the underlying rocky mantle, then models are required which describe the complex relationship of the land surface and the layers: the regolith-terrain (or R-T). The essential construct must merge the infrequent observations we are limited to with these regolith-terrain models. It ranges from imposed statistical models to conceptual models that describe spatial and temporal processes of landscape formation. We describe a modelling concept which both captures important three-dimensional processes on the land surface and in the regolith, which allows integration into computerised models.

The idea builds on existing geomorphological concepts in terms of their usefulness in breaking up the landscape consistently into recognisable and repeatable units. These can then allow more explicit understanding and presentation of terrain information and aid prediction of R-T attributes for resource assessment. These units capture the entire regolith and land surface and are termed regolith-terrain units.

2. THE SOIL-GEOMORPHOLOGICAL FRAMEWORK

The required framework for defining the regolith-terrain must be predictable and consistent and arises from the factors that have influenced the development and distribution of regolith materials. The unit would represent sequences or juxtapositions of regolith and terrain where changes in one regolith-terrain sub-system may impact upon an adjacent or sequential regolith-terrain sub-system.

The 'catena' concept expresses a natural regolith-terrain entity that emphasises the topography and parent material factors as well as geomorphological processes. Adjacent soils and regolith link at different elevations by lateral migration of physical and chemical elements in a geochemical landscape.

The conventional catena is 2-dimensional and consequently is steady-state; it only truly represents a straight thalweg or a hillslope cross-section with straight flowlines. If the catena is viewed broader scales, however, the elementary R-T body can be the geomorphic drainage basin unit, and inter-basin units, of the regolith-terrain system. This generic unit is termed the 'regolith catenary unit' (RCU). Like the catena the RCU consists of a unique aggregation of soil geomorphological properties in a recognisable pattern that makes it distinctive, but in three dimensions.

2.1 The Regolith-Catenary Unit (RCU)

The RCU is adopted as the fundamental organisational unit in the soil geomorphic landscape, which, as it equates with the hydrological drainage basin, neatly agrees with the concept of a fundamental functional landscape unit at the same scale (Figure 1).

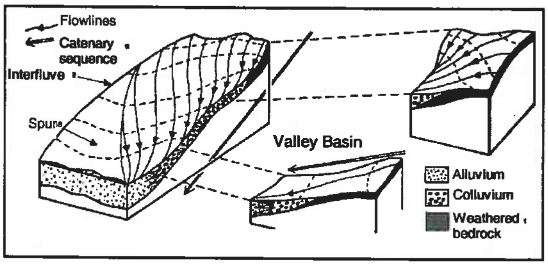

Figure 1. Cross sections of the Regolith Catenary Unit (here depicted as the 'Valley Basin' unit) showing surface process and catenary relationships in a 3-dimensional form [adapted from Huggett, 1975].

The material components of the RCU are the mineral skeletal material, the soil plasma and the soil solution. The processes are those of the pedologic system, as defined by [Simonson, 1959]: addition, removal, transfer (translocation) and transformation of materials, as well as the hydro-geomorphic processes of the hillslope surface and near-surface.

The lateral boundaries to the conventional catena cannot be defined. However, the boundaries to the RCU can be defined. They are perceived to be 'fuzzy', as the materials and processes of one RCU component will merge, gradually or otherwise, with adjacent components.

As the functional soil geomorphic unit, the RCU relates to functional land use systems. Therefore, it may be possible to equate the RCUs to functional management units for site specific management.

The main advantages of developing regolith-catenary units are:

- they possess explicitly defined elements and boundary conditions,
- they are functional, 3-dimensional, open geomorphological systems,
- they conform to an open system of energy and matter flux and conservation,
- the relationships between elements and boundaries can be established through empirical hypotheses and conceptual models,
- their dynamics of form and process may be simulated by computerised terrain modelling.

The topographic imperative to this model is that the third dimension provides a hypothetical component of water and solution/suspension movement. If one assumes conductivity of surface and subsurface water to be equal in the x and y directions then the flowline path will be determined entirely by slope gradient and shape. Hence concavity leads to flow concentration and convexity to flow divergence in both profile and plan curvature. In addition, there will be convergent *infiltration* and divergent infiltration. This is the essence of terrain analysis through digital terrain modelling.

This view of the RCU requires:

- boundary constraints: surface, watersheds, weathering front, fresh bedrock or 'non-regolith',
- that it forms part of a more extensive (hierarchical / holarchical) regolith-terrain system network,
- that it functions as an open natural system (endorheic drainage basins (internally draining) can also be accommodated),
- that it can be quantified.

The definition of an RCU is therefore:
An area of the earth's surface encompassing a volume of earth surface materials which is delineated by defined surface drainage features and represents a characteristic system of soil-geomorphological processes.

3. RCU COMPONENTS

RCUs can be (see Figure 2):

- open drainage features broadly termed 'valley basins' (RCU_{vb}),
- closed drainage features, or 'closed basins' (RCU_{cb}),
- crestal inter-basinal units, or 'summit surfaces'(RCU_{ss}), e.g. hill crests (RCU_{ssc}), ridge crests (RCU_{ssc}), plateaus (RCU_{ssp})
- other inter-basinal units, or 'inter-basins' (RCU_{ib}), divided into two subsets: erosional

(RCU_{ibe}), e.g. spur-ends, cliffs, and depositional (RCU_{ibd}), e.g. floodplains, terraces

Delineation of any of these units is scale-dependent, particularly upon the grain of the investigation and data resolution.

The most important and dynamic of the RCUs is the valley basin (RCU_{vb}), this represents a three-dimensional catena. It is the fundamental pedogeomorphic unit of the terrestrial landscape, which dominates in erosional landscapes, and also commonly occurs in predominantly depositional and residual landscapes.

The identification and delineation of the RCU_{vb} is scale-dependent but generically it has (Figure 2):

- a drainage outlet to a subsequent drainage system,
- a dominant *profile* (long) axis which has a *proximal* end (the crest of the headslope) of higher altitude than the *distal* end (the drainage outlet at either the drainage confluence or at the higher order drainage floodplain margin), and a shorter, sub-dominant *cross* (short) axis that is generally normal to the profile axis,
- relative relief between the proximal and distal ends greater than 5% of its profile axis (the relative relief of the valley basin maybe more than that of its profile axis),
- its boundary defined by incipient water-shedding slopes (*ssc*) which encircle the drainage basin,
- a *core* (*vbc*) defined by the thalweg(s) of the surface drainage features,
- a predominantly water-concentrating concave plan profile landform,
- surface and sub-surface water-concentrating drainage processes,
- simple or convexo-concave sideslopes (*vbs*),
- predominantly 'transitional' (erosional-depositional) slope processes, with erosional processes dominating the peripheral regions and depositional processes dominating the core (drainage line) regions,
- an overall size that has resource management functionality, which can be variably defined.

The RCU_{cb} has a similar definition to that of the RCU_{vb}, except that it does not have a drainage outlet to a subsequent drainage system: it is a closed (surface) system, and that depositional processes are more prevalent, particularly around the *sink* region where the drainage concentrates.

The RCU_{ss} is either a level or convex landform with predominantly 'residual' (vertical drainage processes, minimal erosion or deposition) or 'erosional' geomorphic processes, and commonly curvilinear plan form as interfluves, or drainage divides (RCU_{ssc}), although broad plateaux (RCU_{ssp}) may take a variety of plan forms.

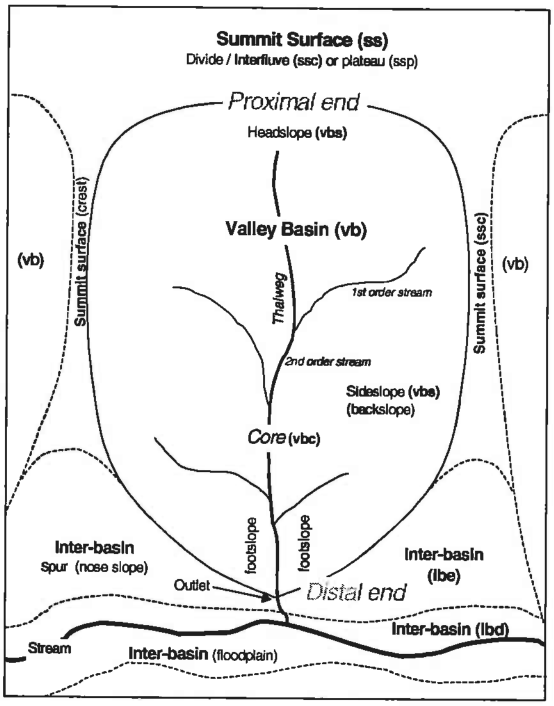

Figure 2. Schematic representation of Regolith Catenary Units: the 'valley basin' and inter-basinal units (summit surfaces and other inter-basin units, such as noses and floodplains).

The RCU_{ib} can take a variety of forms but is conveniently divided into two types:

- *Erosional* (RCU_{ibe}). Dominated by the spur-end (or nose) landform between valley basins and terminating at the subsequent drainage line (or its floodplain). Other erosional forms are cliffs.

- *Depositional* (RCU_{ibd}). Floodplains with complex micro-topography, terraces and ephemeral features as well as large, irregularly formed debris slopes, e.g. talus and scree.

4. THE RCU AND REGOLITH-TERRAIN ANALYSIS

RCUs can be defined digitally through DTM analysis. While this approach is explored here, the resolution and accuracy of the DEM and the original elevation data are ultimately limiting. The satisfactory application of this method is scale-dependent.

It must be also acceptable to delineate RCUs intuitively from aerial photographs and topographic maps, with field checking. The finer the scale of investigation (i.e. the finer the grain and the smaller the extent) the more difficult it is to delineate RCUs precisely. There will always be arbitrary boundaries dependent upon interpretation of landform shape and dominant surface process. This problem is exacerbated at finer scale to a point where delineation becomes redundant. This is occasioned by the 'crisp' categorisation in the concept. A 'fuzzy' classification of RCUs appears more acceptable, but it can be argued to be unnecessary for most broad-scale purposes. Fuzzy RCUs have been developed as part of a regolith-terrain study for the Benarkin Key Area in SE Queensland to predict specific regolith attributes for land management purposes.

The regolith-terrain analytical process is based on regolith-terrain models aided by digital terrain analysis. Regolith-terrain patterns can be predicted from surrogates for regolith attributes that relate to the major factors determining regolith variation in the landscape (i.e. hillslope processes and parent material as well as climatic and biological influences over time – depending on scale). The analysis also assumes that detailed understanding of regolith-terrain relationships in small, representative areas can be used to predict regolith characteristics over wider areas. Representativeness is achieved through exploratory data analysis of relevant landscape components such as geology, soil, catenas, and landforms, remotely sensed data (gamma radiometric data in this case), as well as DTM primary and secondary derivatives.

4.1 A Case Study in a Forested Terrain

The Benarkin Key Area (BKA) study site lies within Benarkin State Forest in south-east Queensland 150 km north west of Brisbane. This undulating and dissected plateau serves as the headwaters to the Brisbane River basin.

The BKA represents the partially dissected, and actively eroding, exhumed Tertiary geomorphic surface, modified by a remnant veneer of weathered basalt in the western and northern parts.

The drainage pattern in the BKA is convergent dendritic, and represents the headward component of an easterly flowing convergent tributary network to the Brisbane River.

The methodological model for the regolith-terrain analysis and regolith attribute prediction comprises a synthesis of four major analytical components that form a regolith-terrain system. The four analysis components are Remote Sensing analysis, Soil-Geomorphic analysis, GIS analysis, and Regolith Catenary Unit (RCU) analysis with attribute correlation.

The first three components were not performed in a linear sequence but come together to allow the RCU analysis and attribute prediction to be undertaken.

This process led to the development of conceptual models for the regolith terrain and the regolith catenary units. The models are based on the conceptual understanding of the pedogeomorphic processes in the landscape and on the regolith-terrain model. These conceptual models were expressed through simple, schematic catenary profile sketches of representative units, and the rules developed for the fuzzy analysis used in the next section.

A DEM for the BKA (20m cells) was created using ANUDEM [Hutchinson, 1989] v4.6.1 using elevation and stream input data from 1:25,000 topographic mapping. The DEM used drainage enforcement and 'sink' removal to render the elevation 'surface' as faithfully as possible as a hydrological surface. A series of DEM terrain derivatives were generated using TAPES-G [Gallant and Wilson, 1996], UPSUM-G (a program within the TAPES-G set) and 'ERA tools' [R. Searle pers. comm., 1998].

Derivative themes were classified into representative classes for efficient data handling and for subsequent input into the fuzzy analysis. The class thresholds were iteratively manipulated to: either a) provide an equal frequency distribution of classes, or b) provide a normal distribution of classes, or c) reflect the trends of the landscape. The method of classification depended on the derivative type and its original frequency distribution.

These classes were combined with remotely sensed data, field survey, and geomorphological data to generate digital models of regolith catenary units, both by 'crisp' classification and 'fuzzy' classification means. It was also done to:

- provide grid cell-based data for terrain attributes in correlation analysis with field regolith attributes,
- provide a fuzzy classification of selected regolith attributes
- present a spatial distribution of fuzzily classified regolith terrain attributes.

This was done through both an explicit modelling with the DTM primary derivatives directly and by 'fuzzy' classification means, using linguistic rules incorporating the DTM primary and secondary derivatives. The components of RCUs, like other regolith terrain data, are not discrete entities: imprecise definition of RCUs (or any terrain features) can be handled effectively by fuzzy logic, and their digital expression can be enhanced in the process.

The fuzzy approach was based on capture of a series of linguistic rules that could be interpreted by fuzzy logic. Separate sets of rules were expressed for each of the RCU components.

The linguistic rules were developed from charting notional relationships between the RCU component response-variable and the terrain derivative explanatory-variables. The resultant digital RCUs were then used in the digital analysis for spatial prediction of regolith variables and to provide digital regolith-terrain maps.

5. SUMMARY AND ANALYSIS

Regolith Catenary Units were readily discerned from aerial photographic interpretation and field observation and could also be determined through digital terrain analysis. The effects of regolith catenary processes are discernible as distinct patterns within the BKA and they can also be predicted using digital terrain analysis. Thus the conceptual pedogeomorphological model of Regolith Catenary Units is applicable to the BKA environment.

Some improvement was possible by combining relevant topographic parameters from the DTM. The 'crisp' depiction of the major RCU components is closer to the reality of their topographical definition than the simple linear boundaries and areal patches drawn from aerial photography. Nonetheless, class boundaries in this classification are still crisp and the classes are discrete.

Definition of the RCU components was particularly suited to fuzzy classification because of the strongly linguistic nature of describing the landform variables that constitute RCUs (e.g. "concave at base", "broadly convex and low gradients", "steepening near the top", etc.). The fuzzy depiction of RCU components (e.g. RCU_{ssc}, Figure 3) resulted from a substantial rule-base which not only improved upon the above 'crisp' classification, but also reproduced the dynamic nature of the model by introducing parameters relating to hillslope processes (e.g. TWI, dispersive area). This is now a model of the soil-geomorphic *system*. Crests are no longer simple watershed lines or uniform areas of one class, but summit regions of influence by hillcrest processes. Similarly, plateaux are presented as summit surfaces defined by surface water and material movement processes rather than delineation of uniform areas.

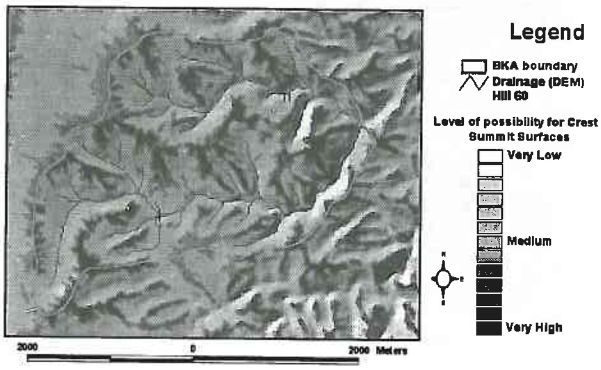

Figure 3. An example of a fuzzy classification of an RCU component (hillcrests: RCU_{ssc})

The boundaries between units are necessarily fuzzy where the rules depicting each component unit weaken. The central concept of each component unit is shown by the strength of colour, which reflects the goodness-of-fit to the rules defining the component. As in reality, a landform unit fades in definition at its margins to merge with neighbouring units. The fuzzy approach produced the best depictions of summit surfaces (RCU_{ss}), crests (ssc), and backslopes (vbs) of the Valley Basins and Valley Cores (vbc) but had difficulties with plateaux, the steepest, concave to straight slopes and Inter-basin (ib) units (Figure 4).

The main reasons for these problems are unsatisfactory explicit linguistic rules to represent these units, an inappropriate grain of the DEM to represent sometimes small and complex land surface forms, and the suite of derivatives from the DEM may not be sufficient to portray the processes and form adequately.

Erosional Inter-basin units (ibe) are the hardest to define explicitly. Many attempts were made to confine ibe's to the vicinity of creek junctions (by 'buffering' distance) and distributive, non-basinal areas (through TWI and Dispersive Area classifications). The result is acceptable, but it does not reflect very well the manual interpretation of these units. Clearly the DEM is not precise enough to render these units distinguishable from Valley Basin slopes (vbs). A higher grain DEM is necessary and further explicit rules, distinguishing non-Valley Basins, are required to enhance the 'ibe' classification.

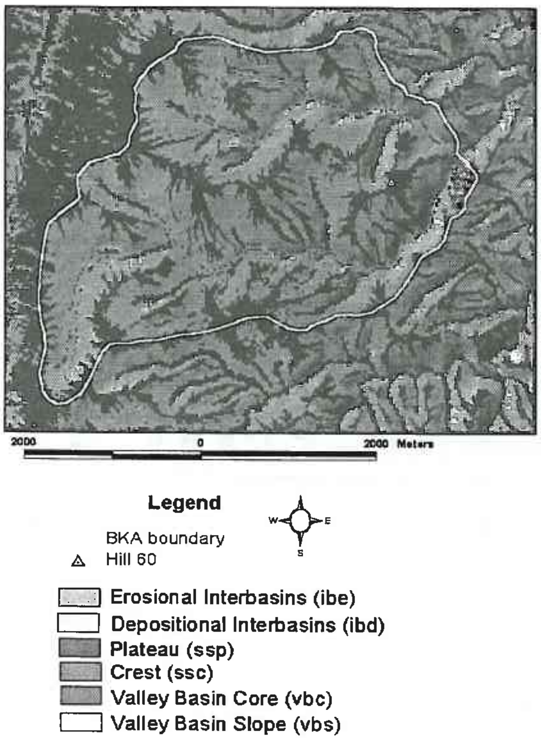

Figure 4. Fuzzy representation of RCUs through digital terrain analysis in the BKA. Original representation and legend is in colour. Hill-shading of the DEM renders a grey colour to the 'transparent' Valley Basin Slopes (RCU_{vb}).

The main aspects to come out of this modelling exercise are two-fold:

- The digital RCU model is repeatable (it was iterated and improved upon several times), and it has the potential to be transferred to other landscapes as it is rule-based and thus generic. It can be used dynamically as a digital model (to recreate and model regolith-catenary pedogeomorphic processes, as well as pedogenesis and landscape development).

- The accuracy and precision of the DEM is not enough to recreate the real landscape at this scale of investigation (between 1:20,000 and 1:35,000 presentation scale), and the variable hierarchical scales of R-T processes therein. The digital model is faithful to the RCU pedogeomorphic concept but not necessarily as faithful to the real terrain at the same time.

6. CONCLUSIONS

Defining RCU components is a convenient and soil-geomorphologically sympathetic way of classifying the regolith-terrain. They can be defined through field survey and aerial photographic interpretation as well as digitally through defining appropriate rules for a DTM. They have been further defined by fuzzy classification means. The successful definition of fuzzy RCUs substantially aids the process of predicting regolith attributes (e.g. regolith depth, top layer depth, top layer stoniness, texture), which was the ultimate purpose of the overall study. The unsuccessful fuzzy definition of some RCUs (e.g. with inter-basinal units) can be potentially confounding for regolith attribute prediction.

The digital, rules-based process is still in need of development and refinement, which will be necessary for any landscape being investigated. For this study, the fuzzy definition of the summit surfaces ($RCU_{ssc;}$ RCU_{ssp}) and the valley basin slopes (RCU_{vbs}) was achieved successfully. The distinction between valley basin cores (RCU_{vbc}) and depositional inter-basins (RCU_{ibd}) needs further refinement, and it is possible that unequivocal definition of erosional inter-basins (RCU_{ibe}) may elude the best attempts with the suite of DEM derivative algorithms currently available. New secondary derivatives for DEMs will need to be developed to do this. Once fully definable by digital means RCUs have the potential to become the basis for any pedogeomorphological stratification of the landscape for predicting regolith-terrain attributes.

The valley-basins and summit surface crests were the only RCU components to be investigated in the field. The validity of inter-basin units and plateaus has yet to be fully explored. The regolith-terrain processes for depositional inter-basins and plateau summit surfaces are not well defined as yet. To do so is a prerequisite to their validation as regolith catenary components.

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