Using Compound Topographic Index to Delineate Soil Landscape Facets from Digital Elevation Models for Comprehensive Coastal Assessment

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EXTENDED ABSTRACT

New South Wales (NSW) coastal areas are under increasing environmental pressure from development and rapid population growth. Soil landscape mapping and land capability assessment have an important role in coastal planning and the development decision making processes.

Soil landscape mapping is a regional planning tool that identifies soil and landscape constraints to development from natural resource management and engineering view points. Currently, this dataset is the only one available for identifying land capability in its broadest sense. More detailed soil landscape information at the hillslope facet level is necessary to identify specific urban and rural land capabilities for the orderly planning of infrastructure, buildings, roads, effluent management and other uses at detailed scales (e.g. 1:25,000 or larger). Derivative maps presenting capability information derived from soil landscape facets and associated data sets can be used to identify land with high versatility and to help anticipate, ameliorate and resolve land use conflicts.

The purpose of this project was to delineate soil landscape facets from digital elevation models (DEM) and soil landscape layers using automated routines in geographic information systems (GIS). Firstly, the Terrain Analysis Using Digital Elevation Models (TauDEM) tool was used to compute flow directions and contributing areas using a D-infinity (Dinf) algorithm (Tarboton, 1997). Secondly, the Compound Topographic Index (CTI) was computed from Dinf contributing areas and slopes using an Arc Macro Language (AML) program implemented in ArcInfo. Thirdly, a soil landscape facet grid layer was generated from CTI grid and soil landscape shape files using automated routines developed in ArcGIS 9.0. These routines derive soil landscape facets from parent soil landscapes layers based on CTI values that underlie the parent soil landscape. Specific focal functions were used to remove speckles or null cells (e.g. gaps at the landscape boundaries) in the output grids. Finally, the output facet grid layer was overlain or linked with other relevant GIS layers and databases to derive thematic information such as capability ratings and feasibility scores for various land use purposes.

The dominant input datasets used in this study were 25 m DEM and soil landscape GIS shape files for all coastal catchments in NSW. Soil landscape layers were prepared from published 1:100,000 scale soil landscape maps and soil regolith data. Unique root strings were created by combining map sheet number (1:100,000 scale) and soil landscape names so that GIS data and other relevant databases could be linked. A facet division file, with instruction of percentage of facets for each soil landscape unit, was needed to break each soil landscape into component facets in the automated facet division processes. In addition, a facet rating file for each soil landscape facet was prepared from relevant soil databases (e.g. SALIS) to provide necessary soil and land attribute information for the land capability assessment.

The Tweed Catchment in northern NSW was selected as a trial study to test the methodology and implementation of the programs. The automated routines were then applied to all rural coastal catchments in NSW to derive soil landscape facets and then make land feasibility maps at facet level. A range of capability and feasibility maps have been produced for various landuse purposes such as standard residential, cropping, grazing and domestic waste disposal.

The methodology developed in this study has been proven to be efficient in delineating most soil landscape facets, particularly in well-defined terrains with an overall agreement about 64%. However, this requires accurate instruction on facet percentages which are traditionally obtained from field survey. Further studies are to examine alternative techniques or terrain modelling to improve the automation and accuracy.

1. INTRODUCTION

This study is a part of the Comprehensive Coastal Assessment (CCA) project initiated by New South Wales (NSW) Government in 2004. The NSW Coastal Strategy formally recognised that the NSW coast is undergoing rapid population growth, demographic change and land use intensification. A key to managing changes and ensuring orderly sustainable development along the NSW coast is to ensure that all land is used according to its capability. The main objective of this project is to provide capability information to assist the regional land use planning process.

Maps of specific soil and land attributes, limitations and hazards, known as derivative maps, can be used to identify areas of high land use versatility—land which is capable of being used for many different purposes. If land is used according to its capability, the potential for land use conflicts can be greatly reduced.

Soil landscape mapping is a regional planning tool that identifies soil and landscape constraints to development from natural resource management and engineering view points. Currently, this dataset is the only one available for identifying land capability in its broadest sense. The soil landscape maps in coastal NSW are published at a scale of 1:100,000. This scale is considered by planners and CCA administration staff to be too broad for many purposes, such as urban and infrastructure planning. More detailed soil landscape information at the facet level is necessary to identify specific urban and rural land capabilities for the orderly planning at a scale of 1:25,000 or larger.

The landforms of catchments, based on landscape toposequence, have been used to define landscape features to aid in soil and land capability mapping (Northcote, 1978, Penock *et al.*, 1987 and Blaszczynski, 1997). They are generally classified into four landform classes representing Shoulder (crest), Backslope (upper slope), Footslope (lower slope) and Level (valley). More recently, a six-landform classification schema has been proposed and will be implemented in FLAG (Fuzzy Landscape Analysis Geographic Information System) model (Summerell *et al.*, 2001), and other classification systems (4 to 11 classes) have also been reported (Carlson *et al.*, 2004). However, these landforms have no direct association with any particular soil landscape and do not include required details to delineate soil landscape facet.

It is difficult and expensive to obtain detailed soil landscape information by traditional means (e.g. soil survey), particularly when large areas are concerned. Emerging terrain modelling and GIS technologies provide potential solutions to depict soil distribution properties at scales nominally approaching soil landscape facet level (at about 1:25,000 scale). One of such attempts was to divide a landscape into discrete units (or facets) and it has been proposed previously in Walker (1991).

The purpose of this project was to delineate soil facets from digital elevation models (DEM) and soil landscape layers using automated routines in geographic information systems (GIS). The project is intended to provide accessible, timely and relevant land and soil capability information for a range of specific land uses for coastal NSW and its hinterland as defined by the mapping area. The capability information will be prepared for use in regional planning.

2. STUDY AREA

The study area includes all NSW coastal catchments except the greater Sydney Metropolitan area (Figure 1). National Parks and State Forests areas are generally excluded. For modelling and mapping purposes, the coastal catchments north of Sydney are grouped as North Coast, while those south of Sydney are grouped as South Coast.

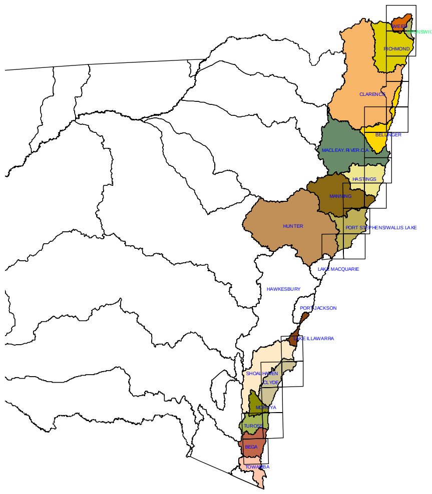

Figure 1. Location of the project area. Color filled areas are coastal catchments, black squares are 1:100,000 map sheet boundaries.

3. DATASETS AND METHODS

The dominant input datasets used in this study were 25 m DEM and soil landscapes for all coastal catchments in NSW. The DEM was used to calculate slopes, flow directions, contributing areas and CTI. Soil landscapes were used as the modelling unit or group within which the soil landscape facets were derived based on the value of CTI. In addition, a facet division file was used to provide instructions for splitting each soil landscape into its component facets. A land feasibility assessment facet rating file was also needed to rank and map the land capability and feasibility at the facet level based on multiple criteria (Chapman *et al*., 2004).

3.1. Soil Landscape GIS Data

Soil landscape GIS layers (in shape file format) were prepared from published 1:100,000 scale soil landscape maps and soil regolith data. Unique root strings (CRA_STRING) were created by combining map sheet number (1:100,000 maps) and soil landscape tag names so that GIS data and other relevant databases could be linked. For example, a combination of map sheet number 9232 and soil landscape tag NCZ creates a unique string 9232NCZ. If a soil landscape unit occurs in more than one map sheet, the map sheet number with the largest area (the dominant soil landscape) was assigned to the new root string. This string is used by the software to group all soil landscapes of a certain type together and perform the facet division. Each root string must also be represented in the facet division file.

The soil landscape layer contained some topologic errors and some very small polygons that may cause the software to crash or incorrectly attempt to divide these small polygons (slivers) into facets. To overcome these problems, the soil landscape data were topologically corrected and very small polygons (e.g. less than 1 ha) were eliminated before modelling.

3.2. Facet Division Files

For each catchment or working area, a facet division file was prepared from the Department's SLADE (Soil Landscape Access Database Environment) database. This was needed to break each soil landscape into its component facets in the automated processes.

The facet division file is a comma delimited (CSV) file that contains instructions for breaking each soil landscape into its component facets. Each line in the file representing a given facet contains these parameters in the following order: 1) parent landscape string, 2) description, 3) facet string, 4) percentage of parent landscape occupied by this facet, and 5) unique integer identifier (ID) for this facet. The IDs range from 1 to 1094 for North Coast, and 2001 to 2498 for South Coast. The lines in the file should be grouped together by landscape, with the upper facets (i.e. hill crests) first.

3.3. Facet Rating File

A facet rating file for both the North and South coasts was prepared from the SLADE database system using Hyperion's query engine (Chapman *et al*., 2004). It provides the relevant soil and land attribute information for the land capability and feasibility ratings. The feasibility assessment approach used in this study has been outlined in Chapman *et al*. (2004).

Data sets not directly related to soil landscapes, or not available from SLADE database, were added where they were readily available. This included acid sulfate soil (ASS) risk class, soil erosion hazard and slope gradient in GIS grid format. These grid data were combined and joined with the facet grid so that every pixel contained all these relevant information needed for land capability assessment.

The facet rating files were exported into DBF format to derive a single set of results for each facet. After the computation of the final capability rates and feasibility scores for each record, it was converted into an INFO file so that it can be linked ('joinitem') with the facet grid value attribute table (VAT) through the facet identification key.

3.4. Compound Topographic Index GIS Grids

A Digital Elevation Model (DEM) with a 25 x 25 m pixel size was available from Department of Lands for the whole of the NSW coastal areas. To ensure hydraulic connectivity within the watershed, the DEM was processed to remove elevation anomalies (e.g. sinks and peaks) that can interfere with hydrologically correct flow. In addition, null (NODATA) cells were filled using focal function (e.g. 'focalmajority') or replaced with zero for large water bodies since the facet modelling program stops at null DEM cells within the working area.

The Compound Topographic Index (CTI) is a steady state wetness index (also named Topographic Wetness Index) and it is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. We used this index for this project because CTI has been proven to be highly correlated with several soil attributes such as horizon depth, silt percentage, organic matter content and phosphorus (Moore *et al*. 1993).

The implementation of CTI can be shown as:

$$CTI = \ln\left(\frac{As}{\tan\beta}\right)$$

where *As* is the specific catchment area expressed as m^2 per unit width orthogonal to the flow direction, and β is the slope angle expressed in radians (Gessler *et al*. 1995).

ESRI's ArcInfo approach for calculating flow direction uses the D8 algorithm, which has disadvantages arising from the proximity of flow into only one of eight possible directions, separated by 45° (e.g. Fairfield and Leymarie, 1991; Quinn *et al*., 1991; and Costa-Cabral and Burges, 1994). This produces very unrealistic results especially producing striped artefacts on very gentle and long lower slopes.

One of the more robust approaches is the D-infinity (D-Inf) algorithm implemented in Terrain Analysis Using Digital Elevation Models (TauDEM) (Tarboton 1997). TauDEM incorporates the DEM analysis tools and functions including pit removal, computation of flow directions, slopes and contributing areas. The calculation of contributing area uses single and multiple flow direction methods. The new procedure overcomes the problems of loops and inconsistencies and performs better than D8 algorithm (Tarboton 1997).

An Arc Macro Language (AML) program (CTI.AML) was used to create a CTI grid layer from DEM and contributing area for each coastal catchment. The contributing area calculated from the D-Inf algorithm was used in the CTI.AML program instead of the default D8 one. The CTI values generated from 25 m DEM using the D-Inf algorithm satisfactory represent the topo-sequence of terrain (e.g. higher values representing drainage depressions; lower values representing the hill crests, ridges and plateaus). The CTI values over the NSW North Coast range from 1.55 to 27.33 with a mean of 10.61, and 4.45 to 28.20 with a mean of 10.12 for the South Coast.

The ArcGIS program was used to produce a merged CTI grid layer for the entire North Coast catchments, and another one for the entire South Coast catchments. Note that there are two types of 'gaps' (null values) in the merged CTI grids. One is the type of gap between catchment boundaries, the other is the type of gap where DEM values are null (e.g. for water bodies). Gaps along catchment boundaries were filled with CTI values calculated from 100 m DEM (resampled to 25 m) using conditional ('con') and 'isnull' grid functions. Other small gaps with null values were filled with Grid focal functions.

3.5. Soil Landscape Facet Production

A Visual Basic Application (VBA) program has been developed to subdivide soil landscape into facets based on CTI values in an ArcGIS Version 9.1 environment. The facet generation program is a batch process which firstly clips a CTI surface and then examines the distribution of CTI values within that soil landscape. A cumulative frequency histogram is constructed so that the values of CTI corresponding to a specified percentage area of the landscape can be determined (Chapman *et al*. 2004). The area percentages have been estimated in the field by soil surveyors as a result of the observations they have made concerning relationships between topographic position and soil type. The CTI values which correspond to any particular facet are then simply given an assigned unique identifier and plotted.

Running the facet division program is a relatively easy process once the input datasets have been prepared. On a high end computer (e.g. Dell Precision Workstation 670) with 2 GB RAM, the program took about 2 hours for medium sized catchments.

Typically only up to 60% percent of soil landscapes can be broken into facets (or can be modelled) based on the facet instruction. This means that there are up to 40% 'gaps' which include facets either can not be modelled or occupy a whole soil landscapes unit. A separate facet grid layer was prepared based on facet identifiers for those gap areas for the north and south coasts. This grid layer was merged with those facet grids that could be modelled (as discussed above) to form a complete facet grid layer.

The merged facet grid may still have speckles (null cells) at the soil landscape or catchment boundaries. These small gaps were filled using focal functions (e.g. 'focalmajority') in ArcGIS Grid module.

The focal process can only fill small gaps depending on the neighbourhood (e.g. 3×3) cells, but is not suitable to fill large gaps (e.g. more than 3 cells). Smooth and smooth edge programs could be used to overcome the problem, but they may cause too much generalisation and loss of detail. The rule is to smooth the edge but keep the necessary details.

Lastly, the merged grids were combined with the acid sulfate soil grid, soil erosion hazard grid, and slope gradient grid so that the combined grid layer contains the capability/feasibility ratings for various land use purposes, such as standard residential, rural residential, high density development, medium density residential, cropping, grazing and waste disposal. The combination was done using the ‘combine’ command in ArcGIS Grid module. The grids’ value attribute table (VAT) table with these capability/feasibility ratings is to be further linked with other feasibility factors (in facet rating file) to produce an overall feasibility score for each land use category for comprehensive coastal assessment.

4. RESULTS AND DISCUSSION

Facet modelling is commonly most successful for soil landscapes with sufficiently pronounced relief for the CTI to readily discriminate terrain differences. It is satisfactory for hilly terrain, for example, as shown in the Figure 2. The yellow lines are soil landscape boundaries. The blue line is an example soil landscape (9333AMZ) where facet modelling was run. The background is the hill-shading DEM. The colours represent various soil landscape facets with red representing crests (40%), yellow upper slopes (40%) and blue mid slopes (20%). These percentages are obtained from the facet division file, that is the facet instruction from soil surveyors.

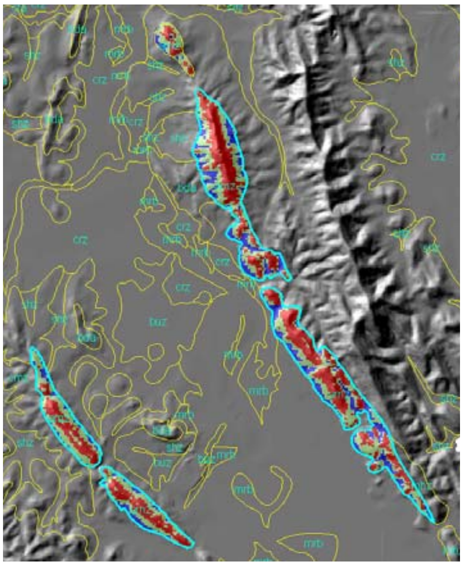

Figure 2. Soil landscape facets derived from CTI values for a hilly soil landscape unit (AMZ).

Figure 3 presents the histogram of the CTI values for this soil landscape. Note that the CTI values have been rescaled to the range between 0 to 1 for this chart. The actual CTI values for this soil landscape range from 6.74 to 20.79 with a mean of 9.23 and SD 1.07.

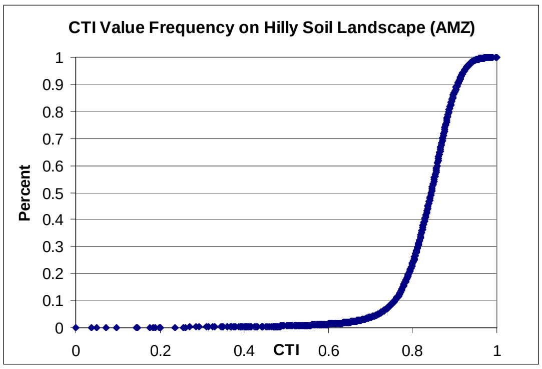

Figure 3. The histogram of the CTI values for a hilly soil landscape (AMZ).

A series of capability and feasibility maps, at soil landscape facet level, were produced for various land use purposes for the whole coastal study area. These, for example, include standard residential, rural residential, medium density residential, high density development, cropping, foundation and domestic waste disposal. Figure 4 presents an example of feasibility map in a section of northern coastal area. These maps can be directly used in regional planning.

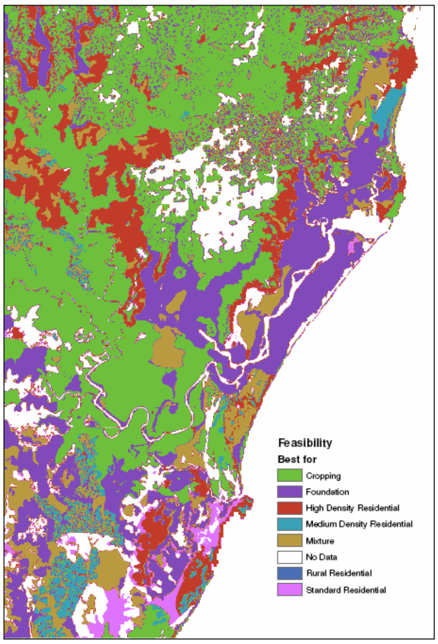

Figure 4. An example feasibility map in northern coastal area.

This project involved several separate processes and each process uses different methodology. It was beyond the scope of this project to assess the accuracy for all these aspects involved. For this study we only assessed the accuracy for the final facet map based on broad terrain categories (e.g. crest, upperslope, lowerslope and plain) and the accuracy was assessed with the use of visual assessment, multi-attribute data and terrain model.

The visual assessment was done by plotting the facet map (with 70% transparency) on top of the hillshaded DEM and comparing the facet with the underneath terrain. This provided a means for quick assessment for areas of interesting. But it is not a quantitative means and is difficult to apply over the whole area.

As an alternative approach to accuracy assessment, we generated 132 random points over the study area on the facet map where we have multi-attribute data which contain terrain information. We obtained the terrain attributes for each point either from manual interpretation (from aerial photo or DEM) or from the terrain attributes in the multi-attribute datasets, some are from FLAG modelling results (Summerell *et al*. 2001). Based on these reference points, the overall agreement for facet modelling is 64%.

Ideally, the accuracy should be assessed against ground truthing. Currently, field validation is underway and will be used to re-assess the accuracy of the facet mapping.

The accuracy of facet modelling is highly dependent on the effectiveness of the facet division instruction and the soil landscape boundaries. The preparation of the facet division file involved intensive manual work, and there were often mismatches between the facet division file and soil landscape or other databases. The soil landscape boundaries may not exactly match with terrains or the DEM may contain abnormal cells. All these are potentially sources of error and need to be carefully checked and corrected.

When computing contributing areas using the D-Inf algorithm, the output grids shrunk by about 2 to 3 cells (cell size 25 m). This resulted in gaps (of about 150 m) along catchment boundaries. This is because that the flow direction can not be calculated for an edge cell because the elevation for any adjoining grid cell is unknown, and may therefore influence the flow direction. The contributing area can not be calculated for any cell adjacent to where the flow direction is not known because the cell with the missing flow direction may flow into that grid cell. Therefore, there are always two grid cells around the edge that are not computed. Sometimes these 'no data' areas extend further into the domain where flow is inwards from the edge, and the contributing area is unknown because the extent of the contribution from outside is unknown. This is an expected result and has been termed edge contamination Tarboton (1997). However, it can be removed by use of focal function or the buffered DEM (e.g. 500m) along boundaries.

Dividing soil landscape units into facets is not a new concept, but the implementation is difficult since it involves complicated spatial analysis and terrain modelling processes. This study has successfully implemented these concepts and produced soil landscape facets for all NSW coastal catchments for the first time.

The successful delineation of soil landscape facets contributed to the key objectives of the soil and landscape assessment component of the Coastal Comprehensive Assessment project being achieved. Maps with information on the capability/feasibility, or physical potential, of land within the coastal study area for a range of land uses has been produced. This key information is supported by a comprehensive set of data resulting from detailed soil landscape mapping over the study area.

The feasibility results and maps present a clear indication of the nature and degree of soil and land constraints affecting various land uses at different locations in the coastal study area. They provide an indication of the consequences and effective economic costs associated with proceeding with different land use scenarios.

The results are in a format suitable for inclusion in the CCA planning process (Topdec). This process will allow the soil landscape constraint information to be combined with other natural resource and socio-economic assessment results to ensure the most appropriate planning decisions are made over the coastal area.

Our proposed further studies are to investigate relevant landform indices (i.e. FLAG, Roberts *et al*., 1997) and relief analysis models (e.g. McNab, 1993, Pennock *et al*., 1987 and Riley *et al*., 1999) to derive facet information for those units that could not be modelled with the current programs. We also intend to incorporate further ancillary GIS datasets (e.g. multi-attribute catchment data, ASS and remote sensing images) are to be used to aid the facet subdivision. More automated programs are also to be developed to accelerate the data preparation and analysis. After quantitative accuracy assessment and evaluation, these methods will then be applied to other inland catchments cross the State.

The main challenge now is to ensure that natural resource spatial products such as those prepared for the CCA process are incorporated more fully into the NSW regional planning process. This will require considerable ongoing dialogue and cooperation between natural resource managers and planners.

5. ACKNOWLEDGMENTS

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