Modelling landscapes using terrain analysis to delineate landforms and predict soil depths – examples from catchments in NSW

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EXTENDED ABSTRACT

A GIS method for modeling landscapes to predict total soil depth and the depth of different soil layers is presented. The method is based on terrain analysis using a DEM and the combined use of the Topographic Wetness Index (TWI) also known as the Compound Topographic Index (CTI) and the Multi-resolution Valley Bottom Flatness index (MrVBF). Examples of the output for several catchments show that soil depth can be predicted at the catchment scale. Only preliminary field checking and validation was carried out, but the results gave values for soil depth and surface soil depths that were within expected values. Several observations about the application of the method are made based on the results for the catchments. For one catchment, the division of the landscape into landform elements is presented and predicted soil depths are related to these landform patterns. Overall the method gives expected values of soil depths, but further validation of the method using field data is required.

This methodology has been applied to a range of catchments in NSW and the results from the Tarcutta Creek, Little River and the Bombala River are presented.

The following information is required from soil landscape mapping and soil data bases:

1) d_5 and d_{50} corresponding to 5^{th} and 50^{th} percentile depths for each soil landscape,
2) dA_5 , dA_{50} and dA_{95} corresponding to the 5^{th}, 50^{th} and 95^{th} depth percentiles for the A-horizons of each soil landscape, and
3) λ_1 and λ_2 multipliers to predict the thickness of the upper B and lower B soil layers. They are estimated for each soil landscape, depending on soil types.

Comparison with the profile descriptions for the map showed that the depth predictions for the surface soil were close to observed values on the upper parts of the landscape (crests, midslopes and footslopes). However, the depths of the surface soils in the depressions and on the floodplains were generally deeper than the observed values.

In the Tarcutta catchment the predictions for several soil landscapes were examined in more detail. As described in Section 2.4, the depth of soil was predicted for each 75 x 75 m pixel using the method in Section 2.1 and the mean soil depth and standard error were calculated within each landform element of the soil landscapes based on the pixels within these defined areas. The soil landscapes were chosen to be representative of different landforms patterns.

These results confirm that the methodology is predicting similar depths to those observed in the field descriptions and to the expected patterns of soil depth in the landscape.

One conclusion is that this method of predicting soil depth distributions based on standard data available in soil landscape reports has the potential to provide valuable information and support to natural resource modeling processes, especially those requiring estimates of soil depth and soil hydraulic properties. However, further field testing and validation of the methodology is required.

A further conclusion is that soil landscape mapping practices should be expanded to include a description of the geomorphic processes occurring in the landscape to support the choice of appropriate landscape models when applying terrain analysis. This is needed to identify the most appropriate landscape model to be applied to predict soil depth.

1. INTRODUCTION

With the advent of computerised systems for storing and processing landscape data it is now possible to model soil landscapes to predict soil depths, landform patterns and the distribution of individual soil types (McKenzie *et al*., 2003, Murphy *et al,*. 2003). In turn this facilitates the preparation of data sets for input into natural resource models, especially those concerned with hydrology, salinity and water flows. The landscape models can be used to predict water storage in soils at the catchment scale (McKenzie *et al.,* 2003). The value in delineating landform elements is that it forms the basis for modelling the spatial distribution of the soil types within complex soil mapping units (Murphy *et al.,* 2003). This paper presents results from the application of landscape modelling using GIS for several catchments across NSW, with emphasis on predicting soil depths. The soil depth predictions are related to the landform elements to check that the predictions are as consistent with values observed in the field descriptions and as expected based on landform element.

2. METHODS

The landscape modelling, or terrain analysis, used to predict soil depth reported in this paper is based on the calculation of two indices from a Digital Elevation Model (DEM). The two indices combined to predict soil depth are the Topographic Wetness Index (TWI), also known as the Compound Topographic Index (CTI) (Wilson and Gallant, 2000) and the Multi-resolution Valley Bottom Flatness index (MrVBF) (Gallant and Dowling, 2003). The concept on which the prediction is based is that the soil formation and the depth of soils will be dependant on the position in the landscape, the area above a point in the landscape, slope and the nature of the parent materials. The method uses a set of observed values for soil depth and ratios of the thicknesses of soil layers to constrain the prediction and incorporate local soil and landscape characteristics (See Table 1). This data is derived from soil landscape reports.

2.1. Calculations for predicting soil depths using a variable weighting of TWI and MrVBF

The following method for determining depth of the soil profile is based on the method of McKenzie et al. (2003). The method presented here has a component that predicts total depth and the depths of different soil layers. The method predicts the depth of soil using two indices TWI and MrVBF, combining these using a weighting function that favours MrVBF on valley flats and TWI on the hill slope.

The total soil depth predicted using MrVBF is:

$$d_{MRVBF} = \begin{cases} 5.5 - 0.93 * MrVBF + \exp\left(\dfrac{MrVBF}{1.82}\right) & \text{when } MrVBF < 7 \\ 46 & \text{when } MrVBF \geq 7 \end{cases} \quad \textbf{(1)}$$

The total soil depth predicted using TWI is:

$$d_{TWI} = d_5 + \left(\frac{TWI - TWI_0}{TWI_1 - TWI_0}\right)(d_{50} - d_5) \quad \textbf{(2)}$$

where, d_5 and d_{50} are the 5^{th} and 50^{th} depth percentiles for each soil landscape (to be obtained from soil landscape mapping), and TWI_1 and TWI_0 are the wetness index values corresponding to d_{50} and d_5 respectively.

The parameter TWI_0 corresponds to the wetness index with specific catchment area of one pixel and 20% slope (i.e. $TWI_0 = 4.8283$). The specific catchment area is defined as area of a pixel per unit contour length (i.e. 25 $m^2.m^{-1}$). The parameter TWI_1 corresponds to the average wetness index of all the neighbouring pixels with MrVBF value less than 1 that surround the pixels with MrVBF equal to the threshold value ($MrVBF_c = 1$), and is typically around 8.

The weighting function for combining the predictions is:

$$TWI_{weight} = \frac{1}{1 + \left(\dfrac{MrVBF}{MrVBF_c}\right)^3} \quad \textbf{(3)}$$

where $MrVBF_c$ is the critical threshold value of the index (recommended value equals 1).

The total soil depth d_{soil} is predicted by the weighted combination of the two predictions:

$$d_{soil} = TWI_{weight}\, d_{TWI} + (1 - TWI_{weight})\, d_{MrVBF} \quad \textbf{(4)}$$

For determining the depth of the A-horizon d_A, the above method is used with the following differences:

- When dA_{MrVBF} exceeds 50 cm, it is constrained to either dA_{95} or 50 cm numerically
- dA_5 and dA_{95} correspond to the A-horizon and not the complete soil depth. The values of these are based on data from soil landscape mapping.

Four soil materials are considered in the model:

1) Depth of the upper B-horizon $d_{B1,}$
2) Lower B horizon d_{B2}
3) Lower soil layer d_Z as determined by the depth of soil profile constrained at all pixels up to 6m (d_{soil} is always < 6 m)
4) Lower soil layer d_Z as determined by the difference between the total soil depth and the sum of d_A, d_{B1} and d_{B2}.

The thickness of the B1, B2 and Z layers are computed as:

$$d_{B1} = \lambda_1 d_A \text{ such that } d_A + d_{B1} \le d_{soil} \quad \textbf{(5)}$$

$$d_{B2} = \lambda_2 d_A \text{ such that } d_A + d_{B1} + d_{B2} \le d_{soil} \quad \textbf{(6)}$$

$$d_Z = d_{soil} - (d_A + d_{B1} + d_{B2}) \quad \textbf{(7)}$$

where λ_1 and λ_2 are the parameters that are used to predict the thickness of the subsoil layers based on the thickness of the A horizon. These vary according to soil type. Typically the λ values are between 1.2 and 1.5 for duplex soils with deep A horizons and 4 to 5 for more clayey soils derived from basaltic parent materials.

2.2 Sources of soil data

The following information is required from soil landscape mapping and soil data bases:

4) d_5 and d_{50} corresponding to 5th and 50th percentile depths for each soil landscape,
5) dA_5, dA_{50} and dA_{95} corresponding to the 5th, 50th and 95th depth percentiles for the A-horizons of each soil landscape, and
6) λ_1 and λ_2 multipliers to predict the thickness of the upper B and lower B soil layers. They are estimated for each soil landscape, depending on soil types.

2.3. Division of the landscape into landform elements or facies.

The landscape was divided into landform elements or facies using a combination of FLAG (Summerell 2003, 2004) and MrVBF (Gallant and Dowling, 2003) as described by Summerell *et al*,. (in press). Terrain analysis was applied to the catchments using the 25m digital elevation model (NSWLIC 1999) to derive the FLAG and LF6 terrain landform units. The terrain analysis method uses digital elevation data to delineate major landforms of catchments. For hill slope areas the FLAG landforms method is used to define landscape topo-sequences of concave and convex breaks of slope (Summerell 2004). These break of slope positions significantly affect contributing cells in the accumulation algorithms used by FLAG landforms. FLAG uses these points to delineate four major landform types: (a) ridge tops and upper slopes, (b) mid slopes, (c) lower slopes and (d) in-filled valleys and alluvial depositions (Summerell *et al.,* 2004, Summerell *et al.,* 2003). In this study further definition of valley bottoms features were delineated using MrVBF (Gallant and Dowling, 2003), as this index is specifically designed to map depositional areas within landscapes. Combining the strengths of both methods, MrVBF in valley floors and FLAG landforms in the hill slopes, is an overall better landform delineation procedure. The procedure that identifies 6 landform categories LF6 which generally represent a hill slope catena as (1) ridge tops and upper slopes, (2) mid slopes, (3) lower slopes, (4) valley fill in upland landscapes or depressions, (5) rises in lowland alluvial fill or long gentle sloping foot slopes and (6) large expanses of in-filled valleys and alluvial depositions. By combining MrVBF and the FLAG landforms, classes 4 and 5 become the extra delineated landform features.

2.4. Predicted soil and horizon depths for each landform element

The depth of soil was predicted for a 75 x 75 m pixel, although the pixel size can be varied in the method. For Tarcutta, the mean soil depth and standard error were calculated within each landform element of the soil landscapes based on the pixels within these defined areas. These predictions were compared to the profile descriptions. This method while not validating the landscape model, provides a check that the outcome from the model gives reasonable predictions.

2.5 Application of the method to catchments

This methodology has been applied to a range of catchments in NSW and the results from the Tarcutta Creek, Little River and the Bombala River are presented. These catchments are third order catchments (starting from main rivers) generally in the size range of 100 to 3000 square kilometres. These catchments were selected because of the pressure to provide information on the likely impacts of land management changes on the water flow, salt loads and salinity of the streams from these catchments.

An example of the data sets used in the model is given in Table 1 for the Tarcutta Catchment near Wagga in NSW. The estimates of d_5, d_{50}, dA_5, dA_{50} and dA_{95} are based on the soil landscape profile data. The estimates of λ_1 and λ_2 are also based on the soil profile data.

Soil depth parameters for Tarcutta Sheet

Sum of AREA HA

SLUNIT	Total (ha)	d5	d50	dA5	dA50	dA95	alpha 1	alpha 2
Kurrajong Plain (kp)	2098	3	5	0.3	0.35	0.4	1.5	2
Kurrajong Plain var a (kpa)	496	3	5	0.3	0.35	0.4	1.5	2
Kyeamba Downs (kd)	5153	0.8	1.5	0.3	0.35	0.45	1.5	2
Livingstone (li)	239	0.2	0.8	0.2	0.2	0.25	1.5	2
Lloyd (ld)	35270	0.25	1.5	0.2	0.25	0.3	1.5	2
Lloyd var b (ldb)	2235	0.25	1.5	0.2	0.25	0.3	1.5	2
Malebo (me)	108	0.35	0.8	0.05	0.25	0.3	1.5	2
Tarcutta (ta)	28168	1.5	2.5	0.25	0.3	0.4	1.5	2
Tarcutta var a (taa)	2006	1.5	2.5	0.25	0.3	0.4	1.5	2
Tarcutta var b (tab)	3488	1.5	2.5	0.25	0.3	0.4	1.5	2
Twins Range (ti)	362	0.2	2.5	0.15	0.25	0.35	1.5	2
Umbango (um)	4646	3	4	0.3	0.4	0.5	1.5	2
Veteran (ve)	57633	0.05	0.6	0.05	0.15	0.3	1.5	2
Veteran var a (vea)	1792	0.05	0.6	0.05	0.15	0.3	1.5	2
Wantabadgery (wb)	5223	1.5	2.5	0.2	0.4	0.5	1.5	2
Wantabadgery var a (wba)	1427	1.5	2.5	0.2	0.4	0.5	1.5	2
Wantabadgery var b (wbb)	731	1.5	2.5	0.2	0.4	0.5	1.5	2
Wattle Vale (wv)	241	0.55	0.7	0.3	0.35	0.4	1.5	2
Wheel of Fortune (wf)	3359	3	4	0.3	0.45	0.5	1.5	2
Wheel of Fortune var a (wfa	708	3	4	0.3	0.45	0.5	1.5	2
Yarragundry (ya)	11533	0.25	0.8	0.15	0.2	0.5	1.5	2
Yarragundry var a (yaa)	31	0.8	1.5	0.2	0.25	0.5	1.5	2
Yarragundry var b (yab)	400	0.25	0.8	0.15	0.2	0.5	1.5	2
Yaven (yv)	3107	1.5	2.5	0.3	0.35	0.45	1.5	2

Table 1. Example of soil data input into the model for the area of the Tarcutta Soil Landscape map.

3. RESULTS

3.1 Tarcutta _Predicted depths for different landform elements.

The predicted surface soil depth for the Tarcutta Catchment is presented in Figure 1, and the predicted total depth in Figure 2. A series of field observations were made to check these depth predictions using road cuttings, erosion gullies, creek cuttings and the soil profile data from the soil landscape map. For most of the Tarcutta Catchment the soil data was based on the newly developed 1:100 000 Tarcutta Soil Landscape map (Wild, in prep.), but the soil units from a less detailed soil map are used to predict soil depths in the eastern portion. This change in the detail of soil data available shows up clearly in the prediction of surface soil depth, but is not so noticeable for the total depth of soil. Comparison with the profile descriptions for the map showed that the depth predictions for the surface soil were close to observed values on the upper parts of the landscape (crests, midslopes and footslopes). However, the depths of the surface soils in the depressions and on the floodplains were generally deeper than the observed values.

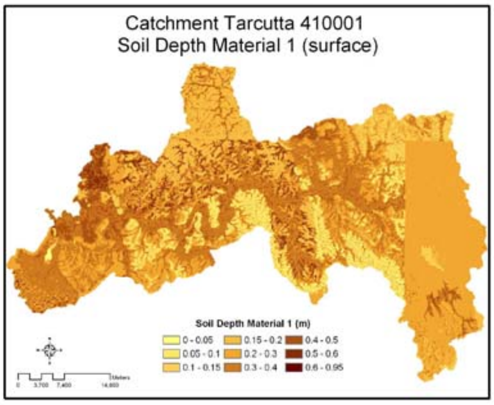

Figure 1. Predicted depth of surface soils for the Tarcutta Catchment. Note the change in the detail due to the different scale of soil data available on the eastern boundary.

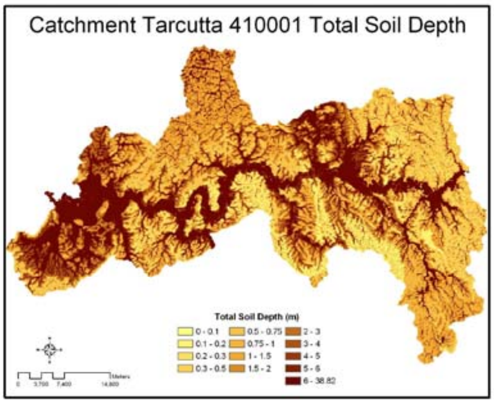

Figure 2. Predicted total soil depth for the Tarcutta Catchment. Note the change in the detail

In Tarcutta, the predictions for several soil landscapes were examined in more detail. As described in Section 2.4, the depth of soil was predicted for each 75 x 75 m pixel using the method in Section 2.1 and the mean soil depth and standard error were calculated within each landform element of the soil landscapes based on the pixels within these defined areas. The soil landscapes were chosen to be representative of different landforms patterns. The soil landscapes chosen were:

- Kurrajong Plain – depositional flats,
- Tarcutta – undulating low hills,
- Yarragundy – rolling low hills and
- Veteran – rolling hills.

The different landform patterns of these soil landscapes are shown in Figure 3. This shows the percentage of each landform element in the soil landscapes. The Kurrajong Plain soil landscape, the depositional flat, is predominantly lower slopes (LF3), valley fill in upland landscapes or depressions (LF4), rises in lowland alluvial fill or long gentle sloping foot slopes (LF5) and large expanses of in-filled valleys and alluvial depositions (LF6). The soil landscapes then grade through to the Yarragundy soil landscape which is the most hilly as indicated by the distribution of landform elements. The Yarragundy soil landscape has a large proportion of ridge tops and upper slopes (LF1), and virtually no occurrences of the landform elements associated with the lower parts of the landscape.

The landform patterns for the soil landscapes are reflected in the predicted total soil depths as shown in Figure 4. The soil depths for the Kurrajong Plains soil landscape are uniformly deep. The predicted soil depths are shallowest for the most hilly soil landscape (Veteran) and show an increase with distance downslope. The other soil landscapes, Tarcutta and Yarragundy, clearly show predicted soil depths that are intermediate between the steepest and flattest landform patterns. These results confirm that the methodology is predicting similar depths to those observed in the field descriptions and to the expected patterns of soil depth in the landscape. The predicted surface soil depths are shown in Figure 5. These show a similar but less clear pattern to predicted total soil depth.

3.2 Little River Catchment

The results for the Little River catchment are shown in Figures 6 and 7. The effect of the soil landscape units are clearly seen in the distribution of the surface soil depths. For example, the shallow surface soils of the siliceous granites can be seen at A, and the deeper surface soils of the granodiorite soils at B. One factor that the landscape model did not predict well was when rock outcrop occurred in midslope positions as often occurred within the Yeoval Granite soil landscapes.

3.3 Delegate River Catchment

The results for the Delegate River Catchment that flows into the Snowy River in south-eastern NSW, are shown in Figures 8 and 9 (Murphy *et al.*, 2005). Mount Delegate in the centre left of the catchment shows up clearly as an area of shallow soils. The deep soils of the flats and alluvial areas are evident. The effect of the different soil landscapes is again clearly evident in the predictions of surface soil depths, but less so for the predictions of total soil depth.

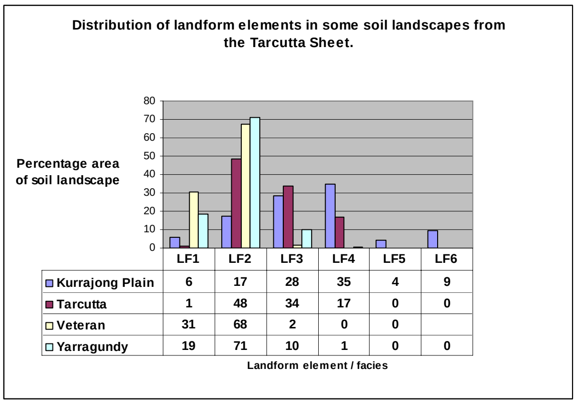

Figure 3. Distribution of landform elements in selected soil landscapes from the Tarcutta Sheet

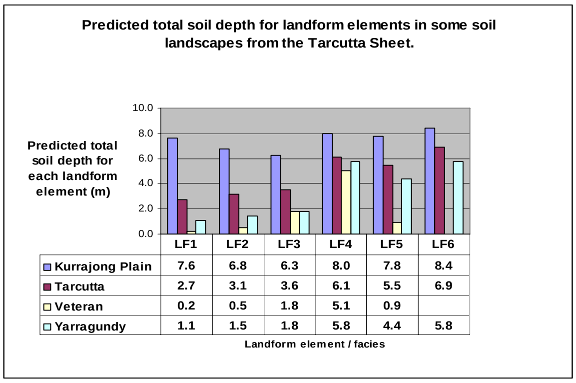

Figure 4. Predicted total soil depth for landform elements in selected soil landscapes from the Tarcutta Sheet

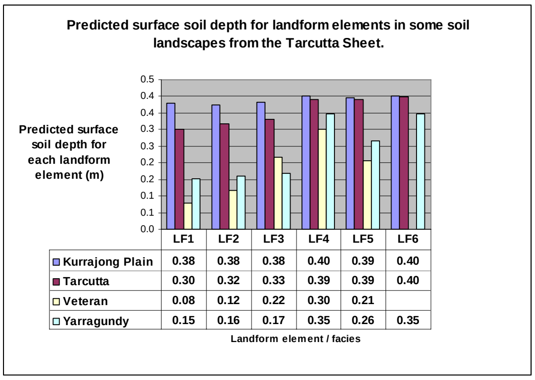

Figure 5. Predicted surface soil depth for landform elements in selected soil landscapes from the Tarcutta Sheet

3. DISCUSSION

These results show that it is possible to make spatial predictions of soil depths as described by McKenzie *et al.* (2003). The predictions are within values observed in the field descriptions and with what would be expected from field experience during soil survey operations. These predictions have only been checked to a limited degree in the field using available field descriptions, road cuttings, gullies and creeks. Some predictions have been checked using

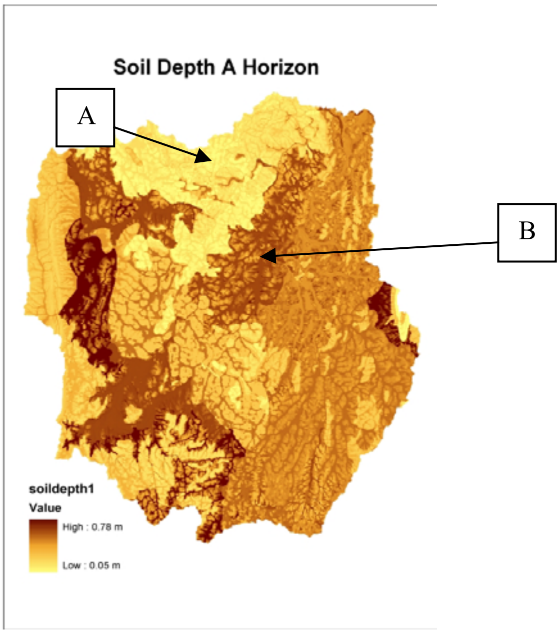

Figure 6. Predicted soil depth of the A horizon for the Little River Catchment.

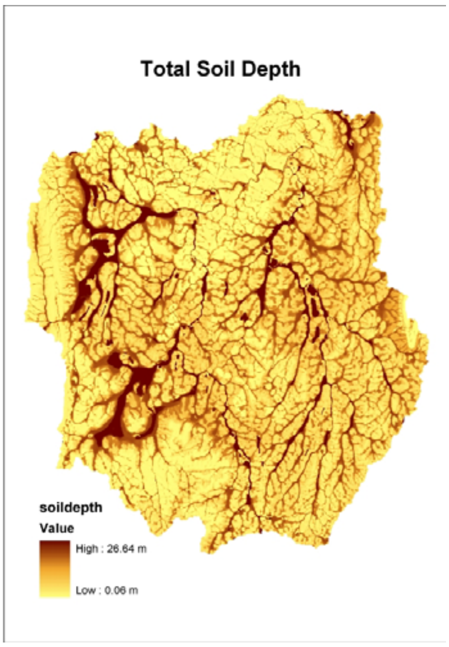

Figure 7. Predicted total soil depth for the Little River Catchment.

available soil profile descriptions, but this is not a valid test of the predictions, because the profile data was used to estimate the input data for the landscape model mentioned in the methodology. However, the check using the soil profile data from the soil landscape maps does

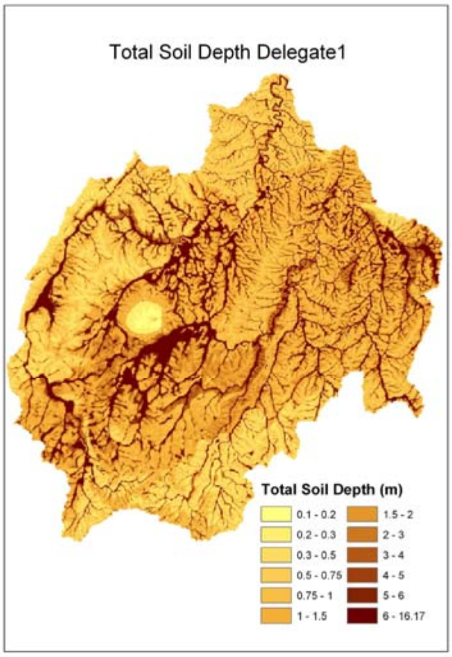

Figure 8. Predicted total soil depth for the Delegate River Catchment.

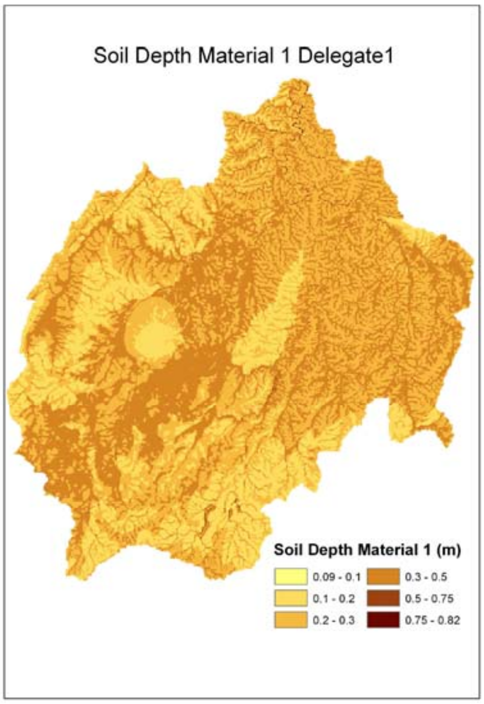

Figure 9. Predicted soil depth of the A horizon for the Delegate River Catchment.

provide a kind of calibration of the methodology.

Several conclusions can be drawn from the experience in using this methodology.

1) The method provides insights into the spatial distribution of soil depth across the landscape. However, further work is required to confirm and validate the predictions made with this landscape model.
2) Standard soil landscape data can provide the information to input into the model to develop predictions of soil depth across the landscape.
3) The effect of different soil landscapes seems to be greatest for predictions of surface soil depths
4) Only one relationship between terrain and soil depth was applied in this model. However, it is reasonable to expect that the actual relationship between terrain and soil depth will vary with geology, geomorphology and landscape history. As McKenzie *et al.* (2003) have identified, the relationship will vary between landscapes that are transport limited and those that are sediment limited.
5) Comparison of the predicted depths of the surface soils for lower parts of the landscape (LF4, LF5 and LF6) to the profile descriptions indicated that these were generally being over-predicted. There maybe a case therefore to investigate ways to prevent this in the future.

One conclusion is that this method of predicting soil depth distributions based on standard data available in soil landscape reports has the potential to provide valuable information and support to natural resource modelling processes, especially those requiring estimates of soil depth and soil hydraulic properties. However, further field testing and validation of the methodology is required.

A further conclusion is that soil landscape mapping practices should be expanded to include a description of the geomorphic processes occurring in the landscape to support the choice of appropriate landscape models when applying terrain analysis. This is needed to identify the most appropriate landscape model to be applied to predict soil depth.

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