USING GIS AND A LAND USE IMPACT MODEL TO ASSESS RISK OF SOIL EROSION IN WEST GIPPSLAND

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The Land Use Impact Model (LUIM) is a spatially explicit tool developed by the Department of Primary Industries Victoria, and the University of Queensland.

The LUIM has an aspatial component that incorporates knowledge of relationships between landscape characteristics and land management practices and a spatial component that uses a GIS to map where these relationships exist or are likely to exist. These data are linked in a risk assessment framework by using a Bayesian belief network (BBN) within the LUIM. The 'soft' data, sourced through workshops with experts and regional stakeholders are combined with the 'hard' biophysical data in this network, so that uncertainties or probabilities in the data are handled in the BBN.

The LUIM application described in this paper shows how it was used to inform the prioritisation of actions for a Soil Erosion Management Plan in West Gippsland. Using the LUIM, maps were produced identifying areas in the West Gippsland CMA region at risk of degradation from six soil erosion processes under current land management regimes. The risk maps were used to identify 'high value' assets to be protected from further degradation as part of the soil erosion management plan.

The LUIM fills a niche in the decision making processes for catchment management. It has the flexibility to be used at a range of scales with whatever data (hard and soft) that may be available. By combining expert opinion with hard data in a spatially explicit risk framework, priority areas can be identified and knowledge gaps highlighted. The LUIM is also adaptable to any issues that have a spatial context where natural resource assets may be threatened by degrading processes.

INTRODUCTION

Natural resource management (NRM) requires understanding of a complex mix of landscape processes and their interaction with human activity. NRM decisions are made in a climate of changing land use and corresponding pressure on water and land resources. Management practices may be modified on the basis of judgement regarding improved outcomes, rather than hard evidence, and land use may not always be an appropriate fit with land capability.

The Land Use Impact Model (LUIM) was initially developed by the Victorian Department of Primary Industries as part of the Victorian Government's catchment indicator program and was used to map likely mismatches between land use and land capability. The LUIM was designed to identify areas in a landscape where specific management practices could cause degradation, and hence to target areas where preventative actions should be taken. The LUIM is based on the work of Smith et al. (2000) which used the concept of identifying "sources of unsustainability" within agricultural land management systems.

Catchment Management Authorities (CMAs) are responsible for identifying and addressing natural resource issues in Victoria. Investment in each catchment management region is guided by Regional Catchment Strategies (RCSs) that are supported by underlying strategies and action plans for particular resource management issues such as soil erosion, salinity and biodiversity. Accreditation of the RCSs and associated action plans is contingent upon the setting of targets and outcomes "in accordance with the agreed framework for national standards" (Commonwealth of Australia 2004). The LUIM application described in this paper shows how it was used to inform the prioritisation of actions for a Soil Erosion Management Plan in the West Gippsland CMA region in Victoria, Australia (**Figure 1**). The method is based on previous work carried out for the development of a soil health strategy in the Corangamite region in Victoria (MacEwan et al. 2004).

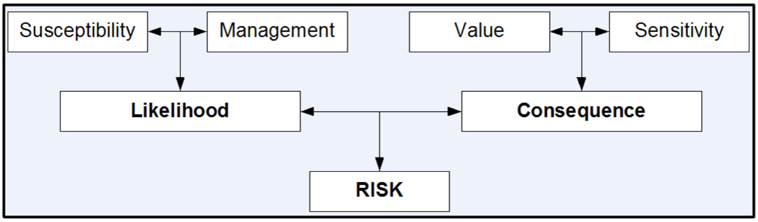

Figure 1 Location of the West Gippsland CMA Region in Victoria

Soil erosion occurs naturally in our agricultural landscapes and can be exacerbated by inappropriate land management practices. Soil erosion reduces the productive potential of agricultural land and causes off site problems such as sedimentation and turbidity in rivers and lakes (Charman and Murphy 1991). Reduced river health and water quality can impact on the environment as well as the tourist and amenity value of an area. Soil erosion is therefore an economic, social and environmental issue that needs to be appropriately managed at both farm and regional levels.

The West Gippsland CMA (WGCMA) 1997 RCS identified soil erosion as a significant issue in the region (WGCMA 1997). The main forms of soil erosion according to the RCS are sheet and rill erosion, gully and tunnel erosion, stream bank erosion, landslides, and wind erosion. Based on information from The National Land and Water Resources Audit, the 2005 WGCMA RCS states that soil erosion is widespread in areas in close proximity to the Gippsland Lakes and around the main irrigation district (WGCMA 2005). To guide the future investment in soil erosion issues, the WGCMA need a soil erosion management plan that documents the extent and severity of erosion in the region and prescribes management actions.

Field survey and mapping the incidence of soil erosion is time and cost prohibitive for an entire CMA region. An alternative is to adopt a modelling approach. The Land Use Impact Model (LUIM) uses a risk based approach to map the likelihood of occurrence of a degrading process for an area based on a combination of mapped landscape attributes and current knowledge of landscape and land management interactions. The risk from erosion is then estimated from the likelihood of occurrence and the potential impact or consequence of erosion on on-site and off-site assets.

METHODS

Six soil degradation processes – landslides, sheet, rill, gully, tunnel, and wind erosion – were assessed using the LUIM. The LUIM was designed to operate within the context of a risk framework (**Figure 2**), based on the Australian Standard AS4360 for risk management (Standards Australia 1995).

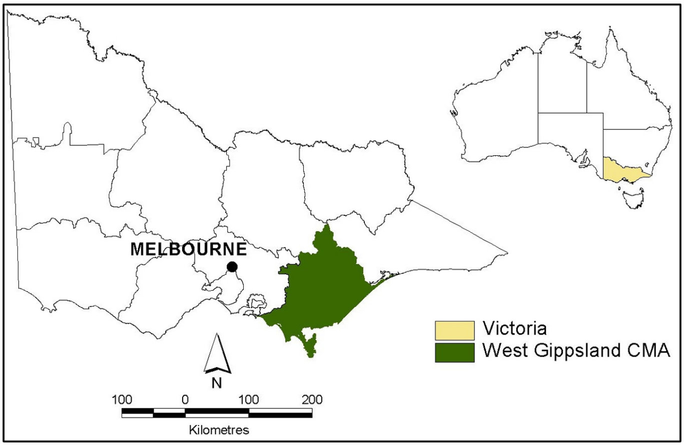

Figure 2 Schematic Representation of Components of Risk Posed by any Hazard

Likelihood, consequence and risk terminology, as detailed in the Australian Standard and with some modifications to suit the specific application of the LUIM, are defined as:

> **Risk:** The product of the **likelihood** that something will happen and the **consequence** suffered if it happens. In this study, risks to soil assets were evaluated in relation to erosion processes.
>
> **Likelihood:** The likelihood that soil will be eroded depends on its **susceptibility** and the role that land use practice may play in causing, aggravating or moderating erosion (**management**). Hence likelihood is a product of the soil's inherent susceptibility to erosion and the imposed land use and associated practices.
>
> **Consequence:** The consequence of erosion depends on how incapacitated or dysfunctional the soil becomes (**sensitivity**) and on the productive and ecological qualities of the soil (**value**). Consequences may also exist for offsite assets (eg. sedimentation, turbidity and nutrient enrichment of rivers and other water bodies). However, only the onsite impacts of erosion are considered in this report.

Each component of the risk framework is mapped separately then combined into a single data layer using a GIS. The spatial data are combined within the LUIM with expert knowledge of land management and landscape processes to produce a spatially explicit output, rating the risk to land assets from various forms of degradation. A flow diagram (**Figure 3**) describes the modelling process.

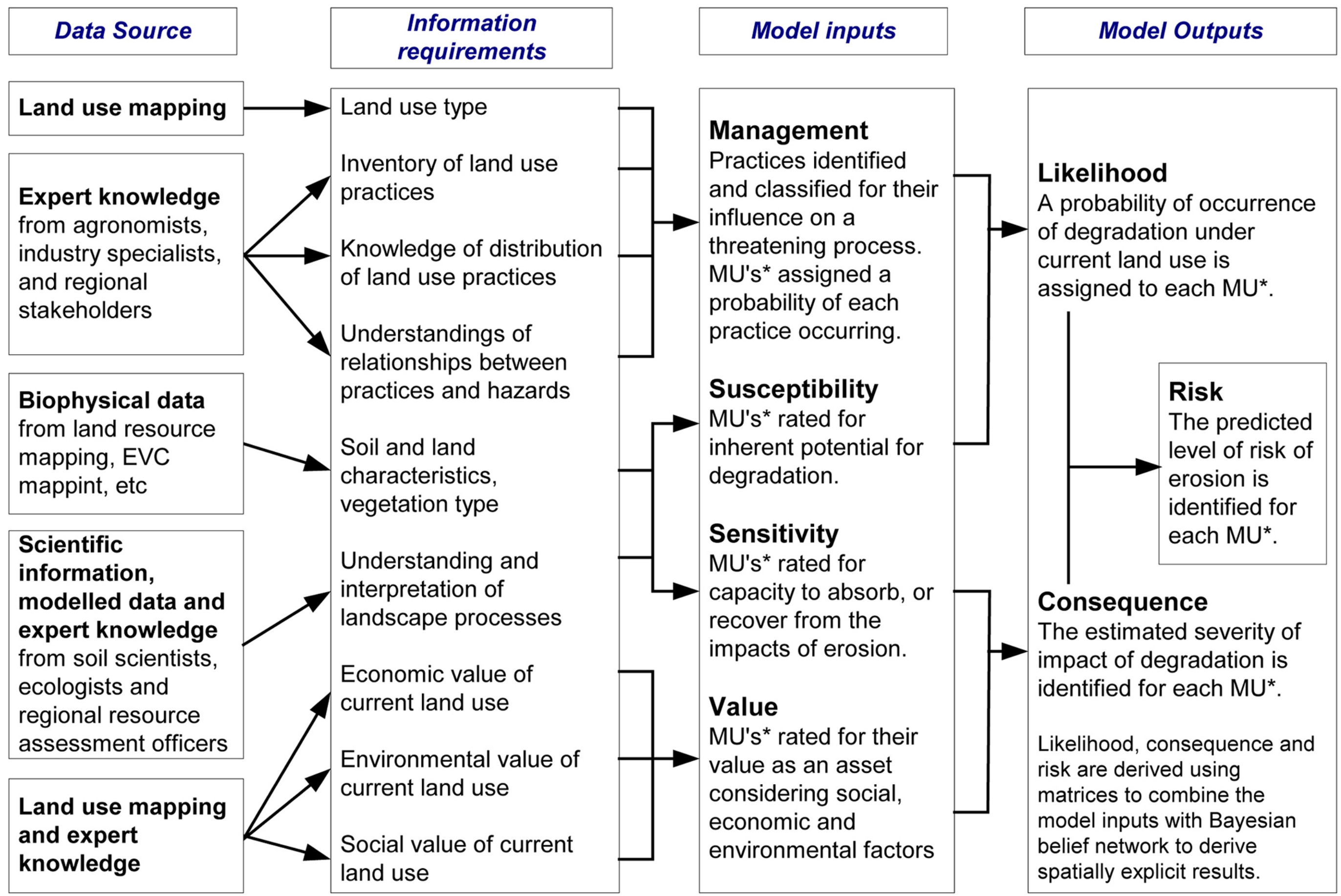

Figure 3 Flow Diagram Describing the LUIM Components and Data Inputs and Model Outputs

* MU = Mapping unit - the primary spatial unit used in the risk assessment derived by combining soil and landford, Digital Elevation Mapping (DEM) and land use data layers in the GIS

The LUIM operates as an extension within ESRI software Arc GIS 9.1, accessed via a toolbar (**Figure 4**). The LUIM GIS toolbar links to Bayesian belief network (BBN) software, Netica V1.05 (Norsys 1997) and to the spatial data (land use and land attributes). Natural resource data and relationships are stored in a BBN constructed around the risk assessment framework (**Figure 5**). The BBN interfaces with the GIS data to allocate ratings to map units (paddocks, polygons etc.).

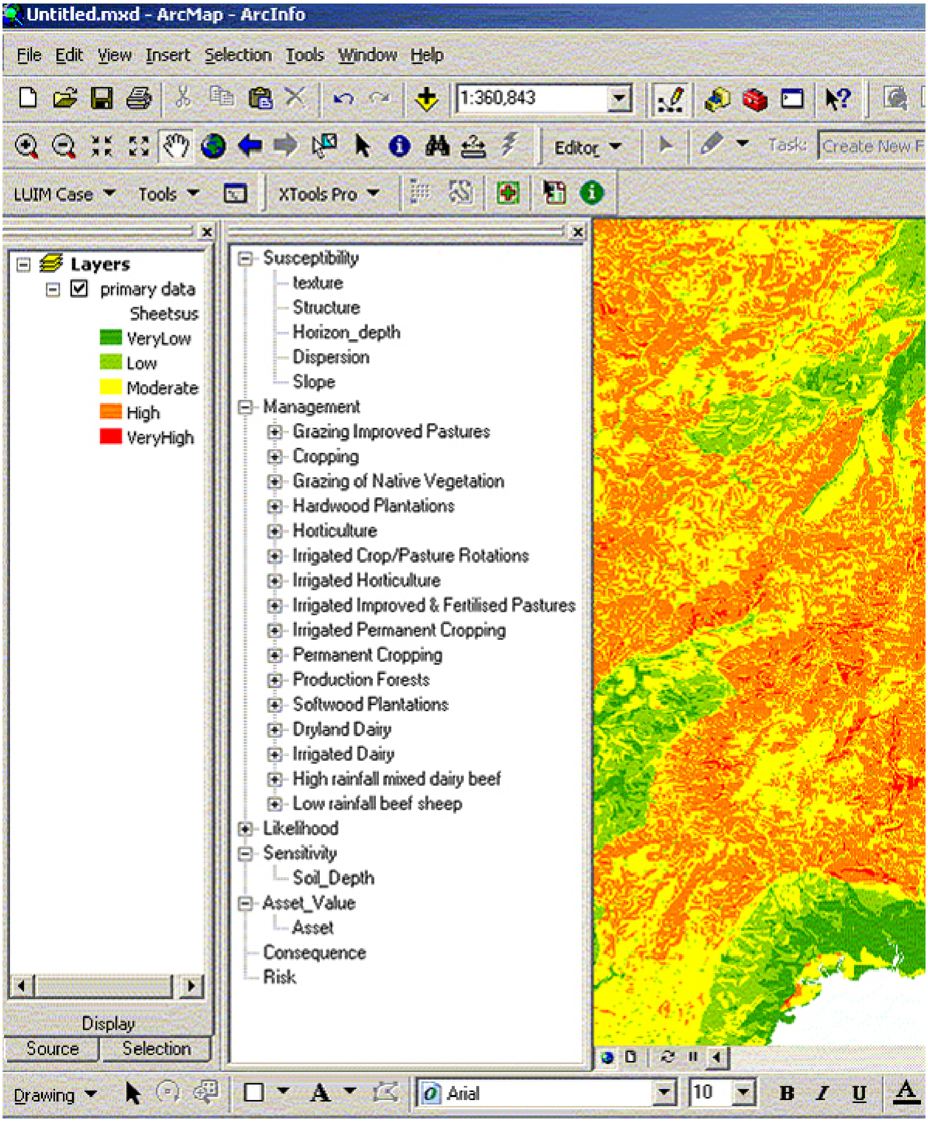

Figure 4 Example of the LUIM GIS User Interface

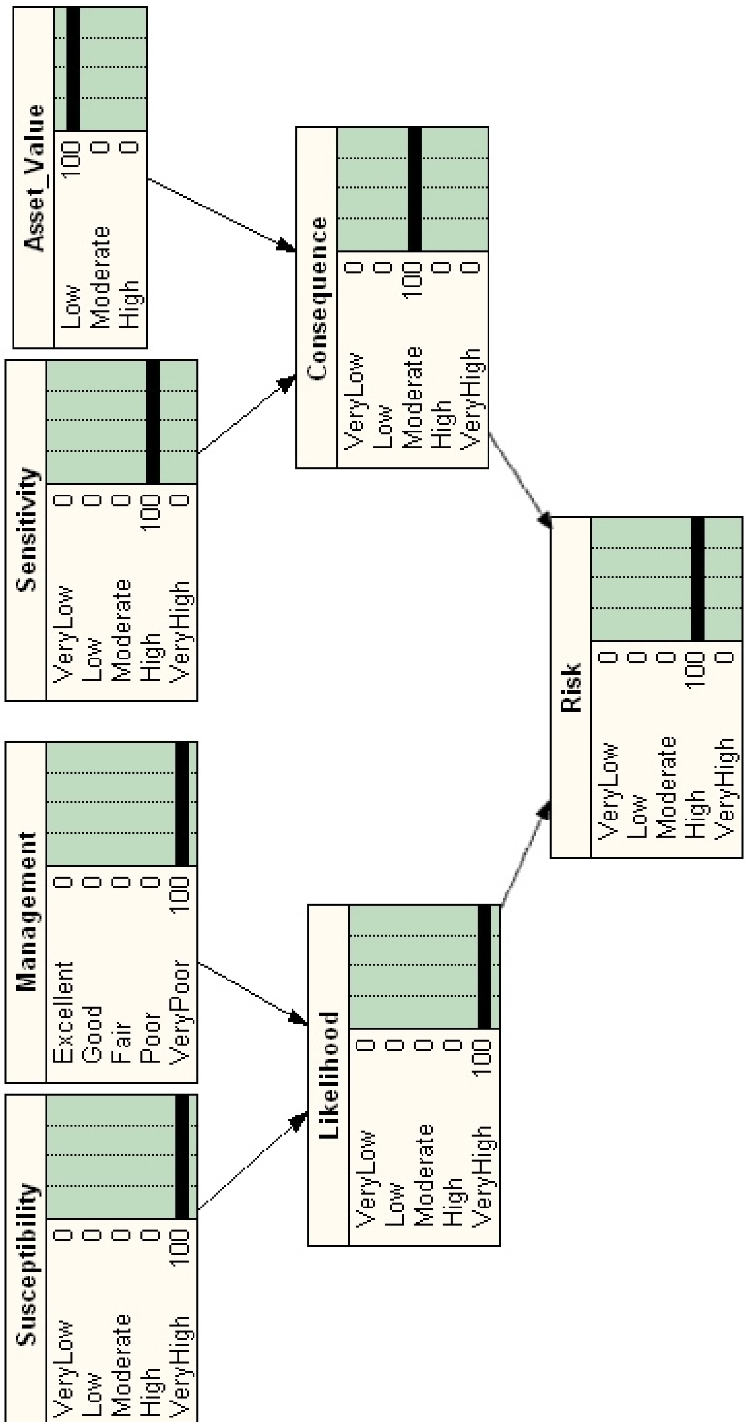

Figure 5 The structure of the Bayesian Belief Network within the LUIM

Bayesian belief networks were originally developed to explicitly account for uncertainty in information used to form decisions to be explicitly accounted for (Cain 2001). A BBN enables system uncertainties to be distinguished from model uncertainties (Ames 2002). We have used the BBN to deal with spatial uncertainty related to management practice information. The example in this paper is for soil erosion, but the basic BBN structure (**Figure 5**) can be modified for any application, according to the degradation issue being assessed, to reflect the criteria and rules used to derive the susceptibility, management, sensitivity and value risk framework components.

The BBN enables information on the spatial variability of land management practices and uncertainty in our understanding of landscape processes, to be 'mapped' explicitly through the model and represented in the results as a probability score for each risk category (very low, low, moderate, high or very high) (**Figure 6**).

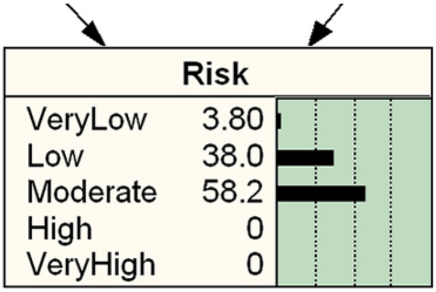

Figure 6 Example of Risk Results in a BBN

The risk rating with the highest probability score in the BBN is used as the measure of risk for each mapping unit and mapped. The combined probability scores of the other four risk classes can be mapped as a measure of confidence in the final risk output. Thus the final risk output is not simply 'high' or 'low', indicating relative risk of degradation across an area, but has an associated probability distribution that can be used to map the uncertainty in the risk results. In the example in **Figure 6**, the moderate risk rating would be mapped as the risk result for the MU as it has the highest probability score. However, the probability score for the moderate rating is only 58%, which means that there is a 42% probability of the risk result being other than moderate for that MU.

PRIMARY MAPPING UNITS AND DATA INPUTS

The primary mapping units (MU) used in the risk analysis for the WGCMA were formed by intersecting soil, landform, digital elevation model (DEM), and land use data in the GIS. The combination of these data sets created a single polygonal layer in which each MU had a set of associated attribute information on soil type, slope and current land use.

The soil-landform information was sourced from a previously mapped 1:100 000 scale land resource assessment of the region (Sargeant and Imhof, 2006). This layer was not available for public land areas of the region and so the assessment was carried out for private (largely agricultural land) only. The DEM was sourced from a state-wide raster data set represented at 1:25 000 scale. A five-class slope polygonal layer was derived from the DEM for the region. Land use information was sourced from a previously mapped 1:100 000 scale land use map (Sposito et al., 2000).

SUSCEPTIBILITY AND SENSITIVITY CLASSIFICATION

Using the soil and slope attribute data, the MUs were classified (very low, low, moderate, high, very high) for their level of susceptibility and sensitivity for each of the soil erosion processes. Susceptibility, defined as the inherent potential for erosion to occur based on landscape characteristics, was assessed using rule tables modified from Elliot and Leys (1991), van Gool and Moore (1998), and Baxter et al (1997). Maps were produced classifying the MUs for inherent susceptibility to each of the erosion processes. The susceptibility information is used in combination with information on management of the land to identify the likelihood of occurrence of erosion for each MU (**Figure 3**).

Sensitivity is defined as the capacity of the soil to recover from erosion if it were to occur. A measure of sensitivity is used in conjunction with asset value (**Figure 3**) to derive a measure of the consequence of erosion to an asset. This information is used to inform the prioritisation of areas for protection from erosion. Sensitivity was assessed using an expert classification in West Gippsland, as there was no set procedure found in the literature that could be applied. Depth of topsoil was identified by regional soil experts as a key factor for measuring sensitivity to erosion. The logic applied by the experts was that productive capacity is more sustainable for a deep soil, i.e. it is less sensitive to erosion than a shallow soil.

The same criteria were used for sheet as for rill erosion, and for gully as for tunnel erosion for both the susceptibility and sensitivity assessment. The factors influencing the occurrence of the combined erosion processes are similar enough to make this a sensible approach to take, one which has been adopted previously in the literature for susceptibility assessments (van Gool and Moore, 1998; Elliot and Leys, 1991; Baxter et al., 1997).

LAND USE AND LAND MANAGEMENT

Land use for each MU was classified according to the land use map (Sposito et al., 2000), that conforms to the Bureau of Rural Sciences (BRS) land use mapping methodology (BRS 2002). The study area is covered by 1:100 000 scale land use mapping, derived from Landsat imagery and refined through extensive field checking. Fifteen land uses were included in the land use impact assessment: grazing improved pastures, permanent cropping, grazing of native vegetation, hardwood plantations, horticulture, irrigated crop-pasture rotations, irrigated horticulture, irrigated improved and fertilised pastures, irrigated, permanent cropping, production forests, softwood plantations, high rainfall dairy, irrigated dairy, high rainfall mixed dairy and beef, and low rainfall mixed beef and sheep.

Information on the uptake and spatial distribution of current agricultural management practices in West Gippsland was not available. In lieu of hard data, regional experts, through a series of workshops, were asked to identify management practices for each land use category that could influence the occurrence of soil erosion and assign combinations of practices a rating for their influence, positive or negative, on the potential for degradation to occur. Practices identified for the land use category 'Irrigated dairy' that have the potential to influence the occurrence of sheet and rill erosion are given as an example:

Irrigation method: spray or flood

Grazing rotation: graze and spell, or set stock

Pasture composition: perennial, sown annual, or annual

Renovation method: cultivation or direct drill

The combinations of practices were ranked from best to worst and then given a rating (strongly negative, moderately negative, weakly negative, neutral, beneficial). An example of the best and worst combinations of practices for irrigated dairy and their ratings are:

Best practice scenario: spray irrigation, graze and spell, perennial pasture direct drill – Beneficial

Worst practice scenario: flood irrigation, set stock, annual pasture, cultivation – Weakly negative

The experts considered none of the dairy practice combinations to be particularly poor for sheet and rill erosion because ground cover is maintained in this region for most of the year even under the worst practice scenario.

The experts were also asked to estimate the distribution of each of the practices for the region, identifying the most common practices through to the least common. For example the estimated percentage of irrigated dairy area where irrigation is applied via a spray rather than flooding was estimated at:

spray: 10 %

flood: 90 %

This regional information does not identify the management of individual paddocks. However, when used in combination with the spatially explicit land use data, the estimated practice distributions were used to inform the probability of each practice occurring in a MU. Thus for any MU classified as irrigated dairy, there is a 10% chance of the irrigation method being spray, and 90% chance it would be flood. The BBN function in the LUIM incorporates these land management probabilities in the modelling.

ASSET VALUE

A measure of the relative value of land assets across the West Gippsland CMA region is required to enable regional managers to prioritise areas for protection and erosion remediation works. An approach adapted from Heislers and Clifton (2004) was used to identify and assign values to assets in the region. Asset classes were defined using land use categories sourced from the 1:100 000 scale land use map. Each land use category mapped for the region was assigned an asset value rating derived through a workshop with regional stakeholders. Each land use was given a score based on a set of economic, environmental and social criteria (**Table 1**). The scores were grouped into five equal interval classes, resulting in each land use category being classified as having a very low, low, moderate, high or very high asset value. The asset value rating is used in combination with the sensitivity ratings for each MU to derive a measure of consequence (**Figure 3**) for each erosion process.

Value class	Assessment criteria
Economic	Asset/service element directly generates substantial economic activity
	Asset/service element has a high capital value (cost of purchase, construction or establishment)
	Asset/service element facilitates significant economic activity
Environmental	The asset/service is of international, national or regional significance
	The asset is in excellent (environmental) condition
	The asset is rare
Social	Heritage value (The asset has strong cultural significance)
	The asset or its use contributes to maintenance of community (provides significant direct or indirect employment)
	Visual amenity
	Social amenity (The asset/service provides substantial amenity to users (shelter, landscape value/personal wellbeing)

Table 1 Assessment Criteria for Defining Asset Value

LIKELIHOOD, CONSEQUENCE AND RISK

Expert knowledge is used to set the parameters or 'rules of assessment' within the LUIM framework. This enables the user to calibrate how the four spatial data inputs into the risk framework (susceptibility, sensitivity, land management and asset value) are combined within the LUIM to derive measures of likelihood, consequence and risk.

Likelihood of occurrence of erosion under specific land management regimes is rated using a matrix (**Table 2**) adapted from the Australian Standard AS4360 for risk management (Standards Australia 1995). The matrix is used to combine the land management information, which establishes the relationship between on site land management and landscape processes, with the susceptibility information.

	MU Susceptibility				
Management practices	Very low	Low	Moderate	High	Very high
Strongly negative	Very low	Moderate	High	Very high	Very high
Moderately negative	Very low	Low	Moderate	High	Very high
Weakly negative	Very low	Low	Low	Moderate	High
Neutral	Very low	Very low	Very low	Low	Low
Beneficial	Very low	Very low	Very low	Low	Low

Table 2 Likelihood of Sheet and Rill Erosion Occurrence as a Product of MU Susceptibility and Management

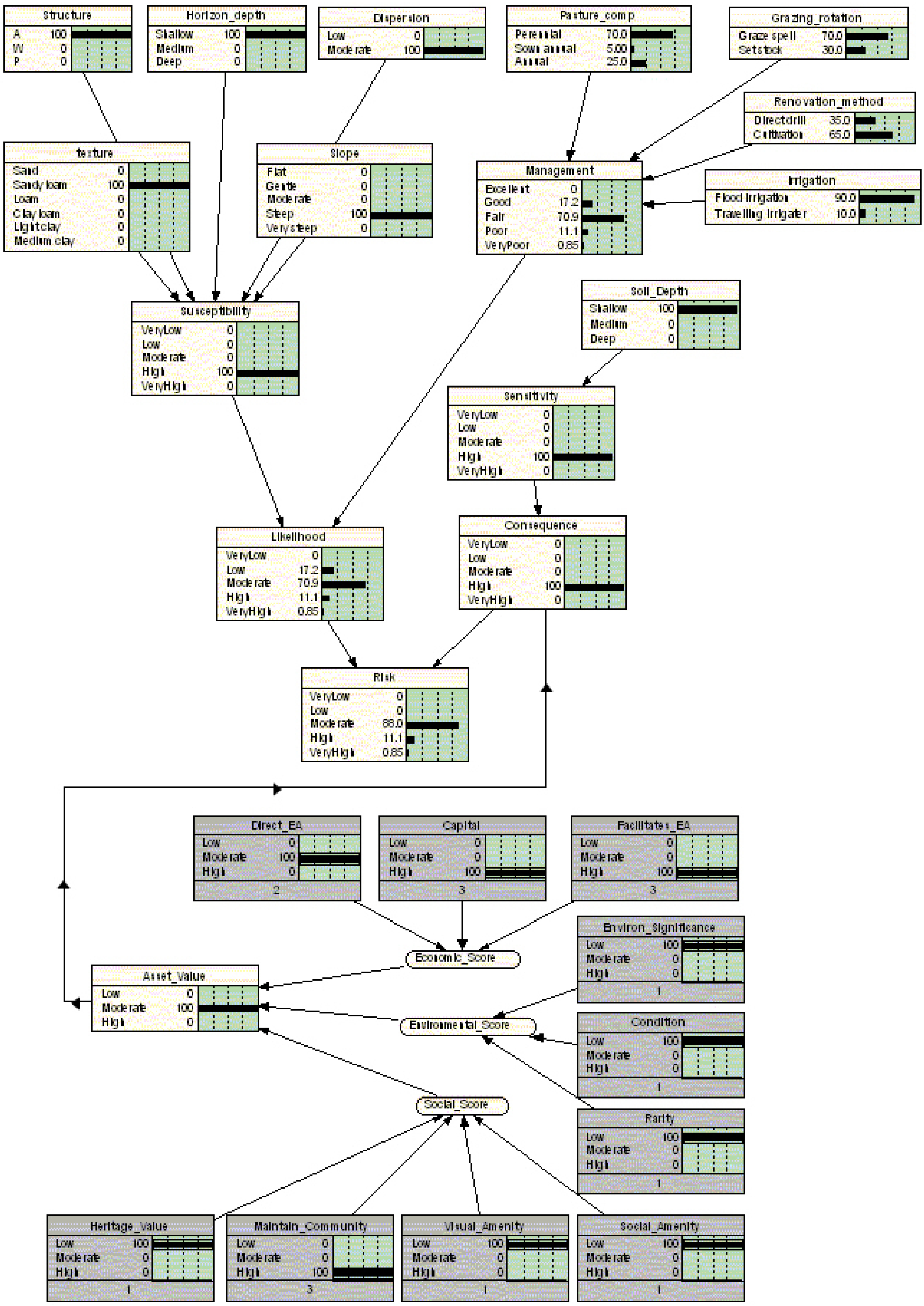

Figure 7 LUIM Bayesian Belief Network for sheet and rill erosion risk under a specific irrigated dairy land management regime, showing an example of results for a single Management Unit (MU).

The matrix structure is embedded within the BBN function in the LUIM but the user decides how the matrix is attributed. For example, in the matrix in Table 2, the combination of moderately negative management and very high susceptibility equals very high likelihood. However, for a different degradation issue the user might rate the same combination as high, rather than very high. The same matrix structure as described in **Table 2** is used to combine sensitivity and asset value to derive a measure of consequence. This matrix structure is also used to combine the measures of likelihood and consequence to derive the final model output, a measure of risk to the asset from erosion.

Once the BBN has been fully attributed and the spatial data linked to the BBN via the LUIM toolbar, the model can be run and results for each component of the risk framework can be derived. An example of a fully attributed BBN (**Figure 7**) shows both the data inputs and results of applying the LUIM to a single MU for sheet and rill erosion under an irrigated dairy land management system.

Each node that is linked to the four basic risk framework nodes (susceptibility, management, sensitivity and value) in the BBN is populated using mapped or estimated biophysical landscape, land use and land management information. The likelihood, consequence and risk nodes are each linked to matrices that that inform the likelihood, consequence and risk results.

RESULTS

Risk maps were generated for each of the erosion processes. The outputs for sheet or rill erosion are presented here. For comparison, maps of the susceptibility (**Figure 8**) to, and likelihood (**Figure 9**) of, sheet or rill erosion occurrence are presented with the results of the risk assessment mapping (**Figure 10**).

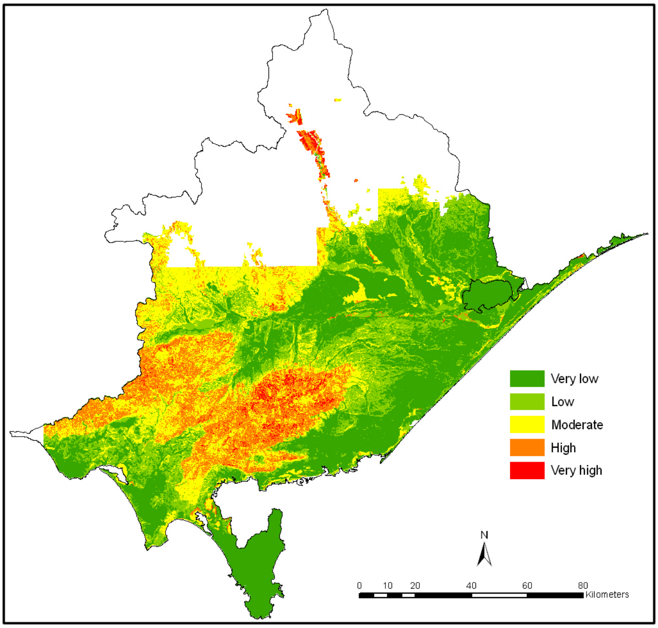

Figure 8 Susceptibility of MUs to Sheet or Rill Erosion

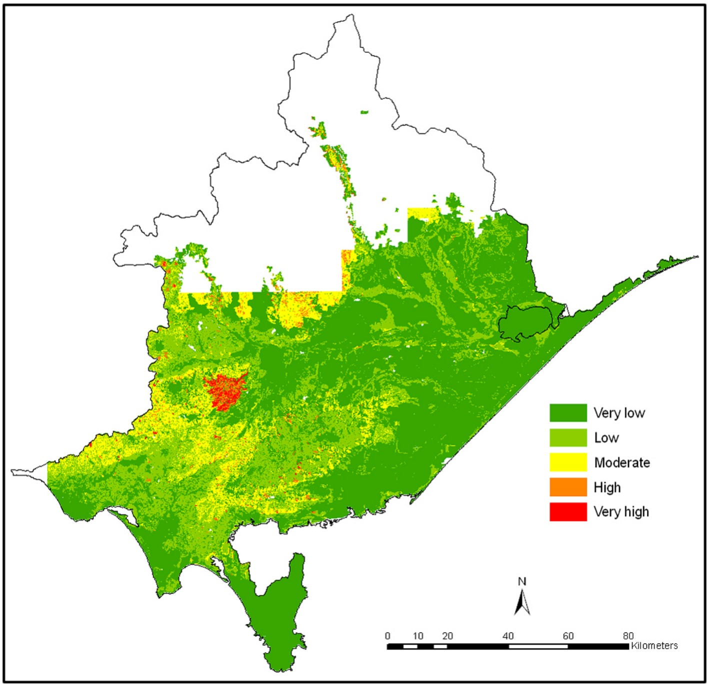

Figure 9 Likelihood of Occurrence of Sheet or Rill Erosion

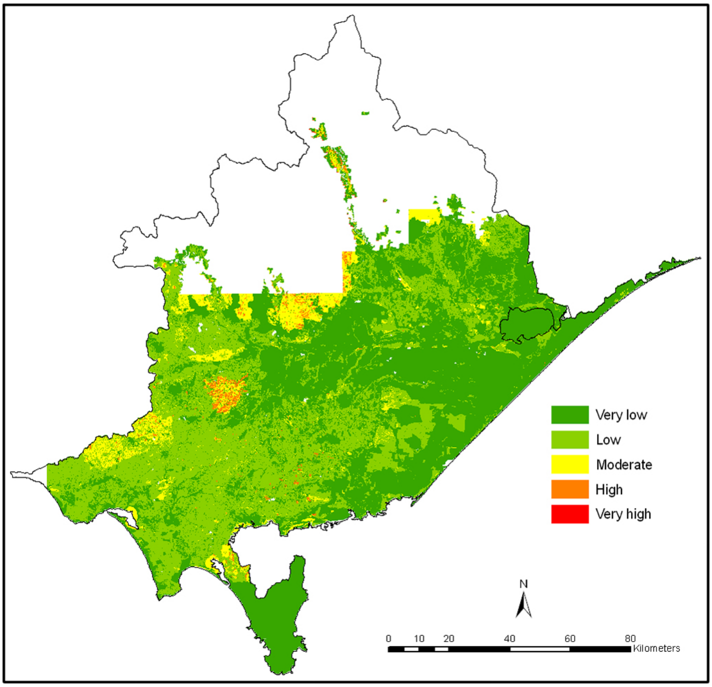

Figure 10 Risk from Sheet or Rill Erosion

DISCUSSION

The map of susceptibility to sheet or rill erosion (**Figure 8**) identifies areas within the West Gippsland CMA region with an inherent potential for degradation. However, in order to identify the extent of sheet or rill erosion in the West Gippsland region, land management information is required to supplement the susceptibility data.

The likelihood map of occurrence of sheet or rill erosion (**Figure 9**) is a result of the combination of the results of the susceptibility assessment (**Figure 8**) with land management information within the LUIM. The likelihood map differentiates between areas susceptible to sheet or rill erosion that are being managed in ways that minimise erosion and susceptible areas that are being inappropriately managed. A small area within the study area where potato growing is the main industry was identified as having the highest likelihood of occurrence for sheet or rill erosion. It is an area of rolling hills where, according to regional experts, a high percentage of farmers adopt a strategy of tilling the soil up and down slope, which significantly increases the likelihood of sheet or rill erosion occurring.

The final output of the LUIM is a risk map for each degradation issue. The risk map for sheet or rill erosion (**Figure 10**) is the result of incorporating a measure of the consequence to the land asset of sheet or rill erosion, with the likelihood outputs (**Figure 9**). The likelihood map can be used to inform natural resource managers of the potential extent of sheet or rill erosion under current land management across a region and the risk map enables prioritisation of these areas based on their economic, environmental or community value.

The risk results are mapped in categories from very low to very high within each class for each map unit but are derived from a probability distribution. This is useful for identifying areas classified as a particular category where there is high spatial variability within a MU or uncertainty in the land management data. This can serve to identify areas where additional probability distribution data are necessary to provide greater confidence to decision makers.

The BBN function enabled incorporation of a range of hard and soft data into the LUIM, along with spatial uncertainties related to the soft data, such as the estimation of land management distributions. In future applications probability distributions could also be associated with other forms of data, such as soil and landform mapping to represent the spatial variability of soils with mapping units.

Modelling of the potential extent and severity of erosion risk in the West Gippsland region using the LUIM provided information for the development of a soil erosion management plan. Review of the risk maps was undertaken by a panel of regional soil and industry experts. With some revisions, there was agreement that the likelihood maps correlated quite strongly with the panels' knowledge of areas that are actively eroding in the region. The risk maps were harder to review, being a more qualitative product. However, the panel accepted the risk results as useful for prioritising high value assets likely to experience soil erosion. A key focus for future work will be the on site validation of the LUIM outputs.

The LUIM, its associated data and rule sets including expert knowledge, offer a transparent and flexible approach that can be reviewed and revised in future planning, monitoring and priority setting. The challenge we see in the immediate future is in making the approach and its associated products accessible to the natural resource management decision-makers. Enhanced accessibility and continued relevance requires collaboration between the scientists who have developed the information and the purchasers, regional stakeholders and users of the products, involving the end users in the process from the beginning. Potential future uses of the LUIM, associated data and risk results in the region include development of a strategic erosion mapping program for areas identified as high-very high risk, predictive land use change impact analysis, and identification of industry specific best management practices for the region.

The LUIM exploits GIS as an integral tool for decision making for land management. The usefulness of the LUIM lies not so much in the power of GIS but in the ability to accommodate a variety of data about land and its vulnerability and management. Precision of the model is limited by spatial resolution of data, assumptions concerning land management relationships, and lack of specific knowledge of the actual location and adoption of specific practices. We could assert that all of the usual caveats apply, as to other GIS applications, that with more or better resolution data the outputs would somehow be better. However, given the specific task for the WGCMA and the importance of community involvement, better precision of model output data may not make a substantial difference to decision making in the region.

The purpose of the LUIM, as described here, is to produce outputs that can provide focus, spatially, for actions to minimise risk of degradation. The LUIM application really only finds completion when actions on the ground serve to alter practices in a direction that lessens the unsustainability of land use. The steps beyond LUIM are necessarily those involving ground truth and engagement with land managers, so that the model outputs are tested by comparison with the real condition of the land and practices are adapted to protect the soil assets where they are genuinely under threat. Greater precision in model outputs might increase efficiency in selecting areas for action. However, there is a danger that greater precision is mistaken for accuracy, and in this way, the outputs become clumsy prescriptive mandates for land use and practices.

CONCLUSION

A balanced perspective in the use of GIS technology and the corresponding roles for social process will result if there is sound engagement with the community. The LUIM method can serve to provide this balance from the development of rulesets, through the attribution of TBL values to assets, to final engagement on the ground.

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