GIS-based tools for management of pine plantations, Queensland, Australia

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Summary

Two examples of GIS-based multiple-criteria evaluations of plantation forests are presented. These desktop assessments use available topographical, geological and pedological information to establish the risk of occurrence of certain environmentally detrimental processes. The first case study is concerned with the risk that chemical additives (i.e. simazine) applied within the forestry landscape may reach the drainage system. The second case study assesses the vulnerability of forested areas to landslides.

The subject of the first multiple-criteria evaluation (MCE) was a 4 km^2 logging area, which had been recently site-prepared for a *Pinus* plantation. The criteria considered relevant to the assessment were proximity to creeks, slope, soil depth to the restrictive layer (i.e. potential depth to a perched water table) and soil erodability (based on clay content). The output of the MCE was in accordance with field observations, showing that this approach has the potential to provide management support by highlighting areas vulnerable to waterlogging, which in turn can trigger overland flow and export of pollutants to the local stream network.

The subject of the second evaluation was an *Araucaria* plantation which is prone to landslips during heavy rain. The parameters included in the assessment were drainage system, the slope of the terrain and geological features such as rocks and structures. A good correlation between the MCE results and field observations was found, suggesting that this GIS approach is useful for the assessment of natural hazards.

Multiple-criteria evaluations are highly flexible as they can be designed in either vector or raster format, depending on the type of available data. Although tested on specific areas, the MCEs presented here can be easily used elsewhere and assist both management intervention and the protection of the adjacent environment by assessing the vulnerability of the forest landscape to either introduced chemicals or natural hazards.

Keywords: geographical information systems; forest management; decision making; evaluation; assessment; risk; landscape; spatial variation

Introduction

Geographic information systems (GIS) have developed rapidly over the last several decades and they are now widely used for basic spatial analyses (i.e. measurement and overlay tasks), cartographic modelling (i.e. landuse suitability), or the latest artificial intelligence applications (Malczewski 2004). Despite their great capabilities, however, GIS are not widely employed to their full potential. In many activities where spatial data are available, GIS are still used only for basic manipulation and visualisation of georeferenced datasets (e.g. Pettit and Pullar 1999). Regardless of the sophistication of the method or approach employed, the ultimate goal of any GIS-based analysis is to provide support for making spatial decisions (Malczewski 1999). As a result, the integration of geographic information systems with multiple criteria decision-making methods (MCDM) has been extensively explored by many researchers over the last 15 y (e.g. Carver 1991; Jankowski 1995; Malczewski 1996, 1999; Hajkowicz 2002).

Modelling using GIS-based multiple criteria approaches has increasingly been used in the analysis of land suitability (Pereira and Duckstein 1993; Laaribi *et al.* 1996; Ceballos-Silva and Lopez-Blanco 2003; Malczewski 2004), in ecological applications (Store and Kangas 2001; Rouget *et al.* 2003; Gkaraveli *et al.* 2004) or management of natural resources including water (Tkach and Simonovic 1997; Schumann and Geyer 1999; Nath *et al.* 2000; Bhuyan *et al.* 2003). Multicriteria analyses have also been adapted to map the risk of certain phenomena or processes occurring, such as natural hazards (Chen *et al.* 2001), erosion (Bantayan and Bishop 1998; Dragan *et al.* 2003; Sivertun and Prange 2003) and pollution of water supplies (Foster and McDonald 2000; Sivertun and Prange 2003). More recently, GIS have been used in conjunction with specialised hydrological models to assist with data integration, mapping and visualisation (Bhuyan *et al.* 2003; Jain *et al.* 2004; Ropke *et al.* 2004).

In the context of extensive GIS use in many domains, there is little published information on forestry applications, although this industry has been expanding worldwide over the last 25 y. According to the Food and Agriculture Organisation of the United Nations there were almost 124 million ha of plantation forests in the world in 1995, of which 25% were established in tropical regions (Brown 2000). Australia manages 1.3 million ha of plantations; this area is expected to increase over the next decade, making Australia a major timber producer in the Pacific Rim region (NAFI 2004).

To date, GIS-based analysis or modelling of the forestry landscape has been mostly concerned with ecological aspects (e.g. Kangas *et al.* 2000; Nagashima *et al.* 2002), although increasing attention is being given to soil characteristics and their role in forest growth (e.g. Payn *et al.* 1999). Recently, GIS-assisted remote sensing techniques have been used to process data on forest growth or to carry out soil surveys (Coops and Waring 2001; Balzter *et al.* 2003; Riano *et al.* 2004). Other aspects of concern in silviculture are related to hydrological issues such as water availability, quality and flow, as well as waterlogging, which can be significant in low-lying coastal areas. Such processes are typically modelled using specialised hydrological software packages (e.g. Koesmarno 1997; Bubb and Croton 2002; Ticehurst *et al.* 2003), many without the assistance of GIS. Furthermore, GIS-based multicriteria analyses are yet to be widely used for forestry applications, although GIS databases are now commonly available and contain information that could be processed at a higher level. In Australia, for example, collection and recording of detailed information on topography, soil character and silviculture for all government-managed plantation forests has become standard practice. Such information is primarily used for simple visualisation, despite its scientific significance for management and decision making.

This paper presents two forestry examples of GIS-based multiple-criteria evaluations which use available topographical, geological and pedological information to establish the risk of occurrence of certain environmentally detrimental processes. The first case study is concerned with the risk that chemical additives applied within the forestry landscape may reach the drainage system; the second assesses the vulnerability of forested areas to landsliding. Although tested on specific locations, the GIS-based assessments can be easily used elsewhere and assist both management intervention and the protection of the adjacent environment. Significantly, these evaluations do not preclude the use of specialised modelling techniques or programs. In addition, multiple-criteria evaluations can be easy to use and are of value as precursors to modelling as they can identify areas of concern.

Case study 1 — Chemical treatment

Problem description

The subject of the GIS-based analysis was a 4 km^2 logging area located in tropical northern Queensland, Australia (Fig. 1). The area had been recently site-prepared for a *Pinus* plantation using a combination of cultivation techniques — spot mounding on slopes >5% and continuous mounds on slopes <5%. The soil type was classified as a Podzolic, characterised by a shallow loam (0.5–1.0 m) over heavy clay with low hydraulic conductivity; this promotes the formation of a perched watertable in the upper profile. The residual herbicide simazine was manually applied along the planting band at 5 kg ha^{-1} (treated area) to individual sections of the logging area, between 23 December 2003 and 29 February 2004. Simazine was used for control of perennial weeds dominated by thick swards of tropical pasture grasses. This period was characterised by irregular rainfall events, which along with normal breaks in field operations resulted in a mosaic of treated areas throughout the area.

As part of the associated monitoring program, monthly grab-samples were taken from the creek which drains the area (Fig. 1). Simazine concentrations above the aquatic ecosystem trigger-values of 3.2 µg L^{-1} (ANZECC and ARMCANZ 2000) were detected in samples taken on 16 January 2004 and 5 February 2004, whereas samples in the seven months following were below this value. These initial findings resulted in a field inspection

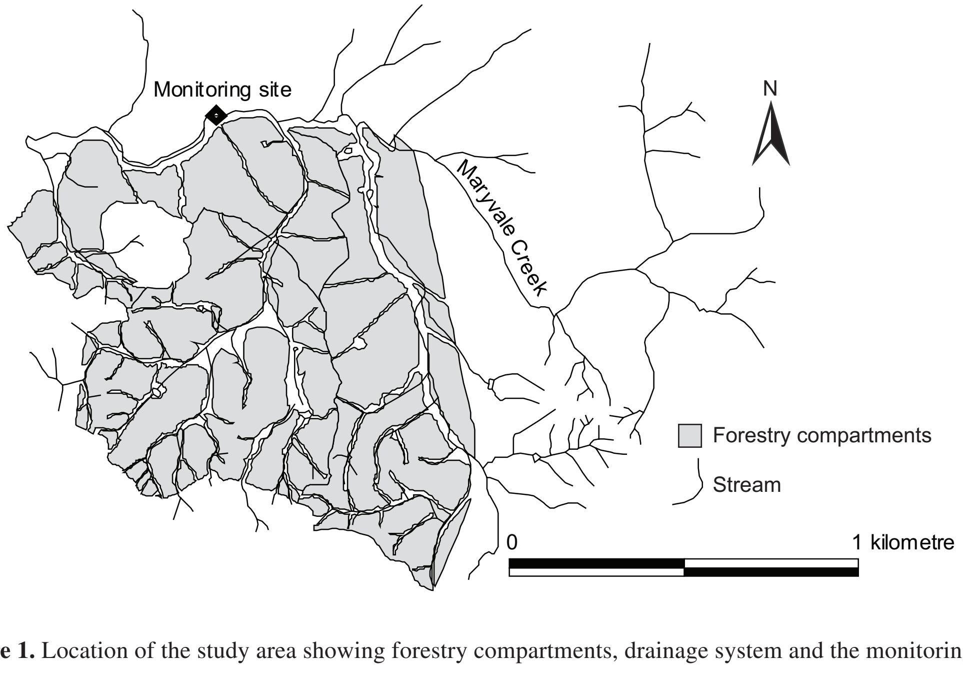

Figure 1. Location of the study area showing forestry compartments, drainage system and the monitoring site

and review of the simazine application procedures along with a proposal to undertake a GIS-based desktop study in order to identify the areas likely to export simazine offsite. Existing data such as topography, soil characteristics, rainfall records and history of simazine applications were made available and used in this investigation. For the purpose of this study, the term ‘vulnerability’ refers to the likelihood that an introduced chemical (i.e. simazine) will be lost from a certain area of land and will enter the drainage system.

Simazine is moderately persistent with a half-life of 1–20 weeks (Meakins *et al.* 1995; Vink and Van der Zee 1997; Bubb 2001; Calderon *et al*. 2004). This high variability is most likely due to the simazine response to various field conditions; for example warm temperatures, high soil moisture, low pH and the presence of sandy material can all increase the rate of simazine breakdown (Meakins *et al.* 1995; Thomas and Piper 2001). Apparently there is little lateral movement of the chemical within the soil profile, and many studies have observed simazine in the top 20–100 cm of soil (e.g. Close *et al.* 1998; Bubb 2001; Thomas and Piper 2001). The low solubility of this herbicide can cause slow release, and the peak of its concentration in soil and groundwater can occur 10–20 days after application. Rainfall, however, can influence this process, as about 90% of simazine is transported in dissolved form (Garmouma *et al.* 1997; Bubb 2001). Rainfall simulations showed that the simazine concentration in runoff can be quite high immediately after application, but can decrease by a factor of 5 and 10 times after rain events which are simulated one and two weeks after application, respectively (Liu and O’Connell 2003). Bubb (2001) found large simazine ‘spikes’ in streamwater to be associated primarily with the first runoff/flood event following application to plantation areas; attenuated stream concentrations (order of magnitude) were measured in following events, for up to six weeks after application. These characteristics are common to many herbicides and are relevant to the design of the GIS assessment.

Method

Design and rationale

The GIS method employed for the assessment of the study area was a multiple-criteria evaluation (MCE) as described by Carver (1991). The geoprocessing was carried out in a vector format and consisted of the intersection of several layers of data; the software employed was ArcView 3.1. The data were normalised and a final weighted score of vulnerability was calculated and plotted.

We considered that an assessment of the morphology and soil characteristics of the area would enable evaluation of the vulnerability to waterlogging, which in turn can trigger overland flow and consequently export of additives. Rainfall duration and intensity are always used in hydrological assessments and modelling (e.g. Foster and McDonald 2000; Ticehurst *et al.* 2003), but rainfall was not included in this MCE as it was considered that precipitation is not directly linked to the propensity of a region to release pollutants. Previous work in these landscape settings has found any major influence on runoff to be via the process of saturated overland flow, whereby a saturated soil profile is the precursor to runoff. As a consequence, the natural setting (topography and soil character) is the main control over the transport of additives to the drainage system, and rainfall will influence only the time and quantity of pollution.

As this MCE was directed to the modelling of natural parameters, the layers included were proximity to creeks, slope, depth to the restrictive soil layer (i.e. potential depth to a perched water table) and soil erodability, which was based on clay content (i.e. little clay equates to high risk). Other factors potentially influencing overland flow such as climate, vegetative cover and stream characteristics (Ward and Robinson 1990; Manning 1992; Wanielista *et al.* 1997) were regarded as quite homogenous throughout the study area and therefore not considered. The final weighted score was the result of the summation of all these parameters; it was not aimed at quantifying the actual overland flow but at visualisation of sites highly vulnerable to chemical transport due to waterlogging and overland flow potential.

Parameters and their weights

The drainage system layer of the GIS was used to create a new layer containing a 100-m buffer centred on the creek (100 m each side), this being the area most likely to waterlog and produce overland flow that would reach the creek; the remaining area further from the stream network was considered of low vulnerability to waterlogging (Fig. 2a). As surface water flow is the main mechanism of exporting pollutants, this layer of proximity to creeks was given a weight of 40%.

The slope layer was generated from 0.25-m elevation contours and was divided into five categories of slope (Fig. 2b). Field observations showed that the gentler slopes of low-lying coastal areas are more likely to waterlog and cause overland flow. This process is referred to as saturation overland flow; it occurs when the soil profile is almost or completely saturated, effectively reducing surface infiltration (Ward and Robinson 1990). Therefore, in the MCE analysis, gentler slopes were considered more susceptible to export of soil additives. The weight of this data layer was set at 40%.

The soil erodability layer, and depth to the restrictive layer, were point layers and therefore treated similarly; using radial function interpolation polygonal objects were created to enable intersection with the other polygon files. It was assumed that the higher the erodability of surficial soils, the higher was the risk of simazine adsorbed onto particles reaching the creeks during rain events. This property, however, was given a low weighting of 10% in the analysis, as simazine is known to be primarily transported in dissolved form (Bubb 2001; Thomas and Piper 2001). If the MCE were to be run for phosphorus, for example, a higher weighing for erodability should be applied as this nutrient is mainly transported by suspended particles. It was also assumed that the greater the depth to a restrictive layer of low permeability, the less likely is the terrain to waterlog and produce overland flow. This layer was also given a 10% weighting.

Results and discussion

Vulnerability mapping

The intersection of the four layers produced a new file containing several thousand polygons, each characterised by a value of slope, a value defining its proximity to the creek (i.e. closer or further

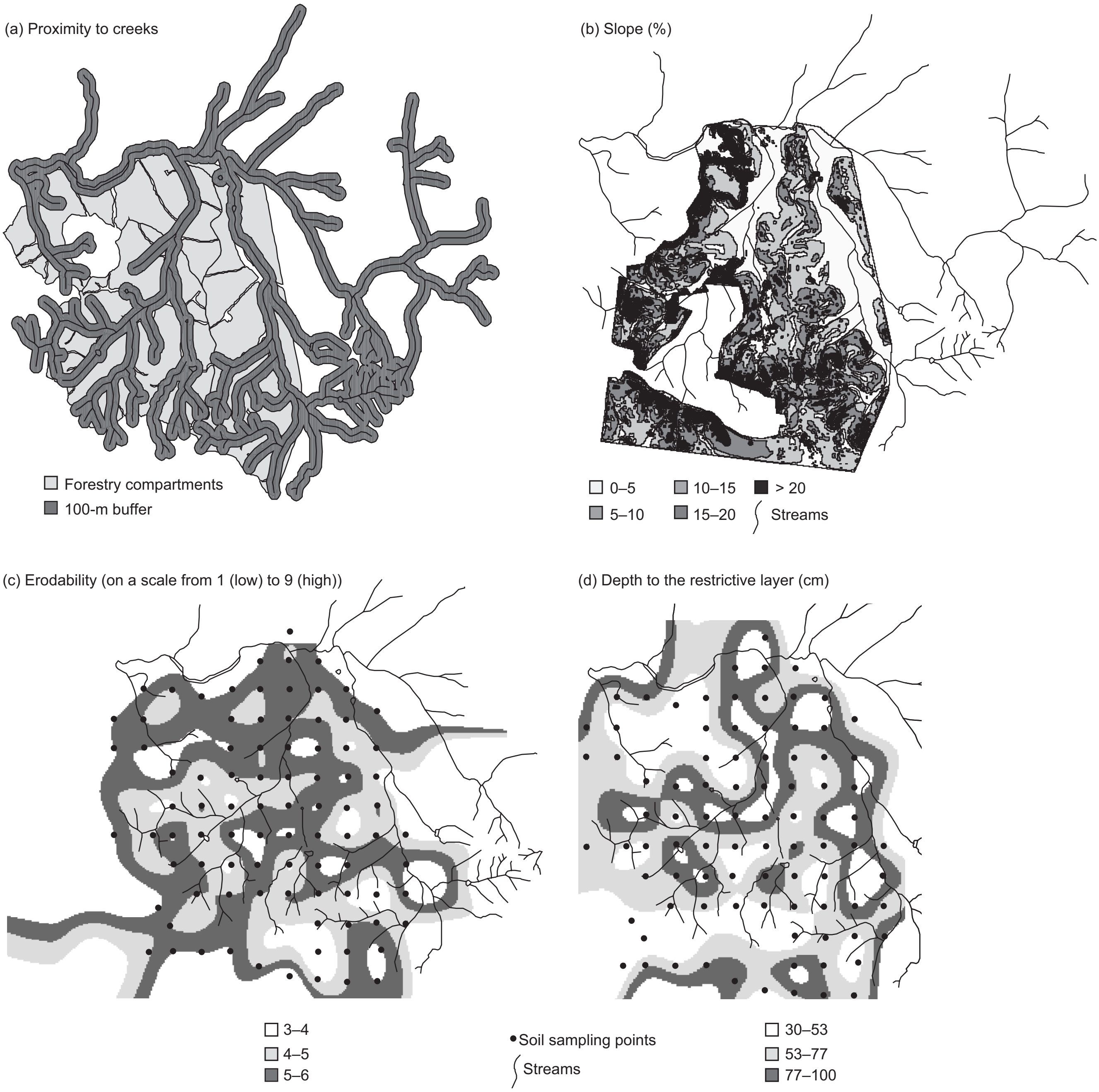

Figure 2. Parameters of the MCE: (a) proximity to creeks in the form of a 100–m wide buffer and (b) slope derived from elevation surveys; (c) erodability and (d) depth to the restrictive layer are based on field analyses and measurements, and are presented as interpolated surfaces.

than 100 m from creek), an erodability value and a depth to the restrictive layer. These values were, however, of different orders of magnitude and, most importantly, were measured in different units. In order to further manipulate the data, these values were standardised, weighted and added to form a new column of weighted scores (Carver 1991). Plotting these scores enabled the visualisation of the combined influence of all parameters considered. The results were in the form of a map of vulnerability to waterlogging, overland flow generation, and simazine or nutrient export to waterways (Fig. 3). The objects of this map were then merged back into compartments to provide plantation managers with an easy-to-use decision-making tool (Fig. 4).

The main advantage of this type of analysis is that the weighted scores can be easily recalculated and the relationship between parameters reassessed when more data are collected; the main disadvantage is that the MCE analysis assumes a linear relationship between parameters, which may not always be the case. However, field observations and measurements can assist identification of any non-linear relationships and improve the worth of the final weighted score.

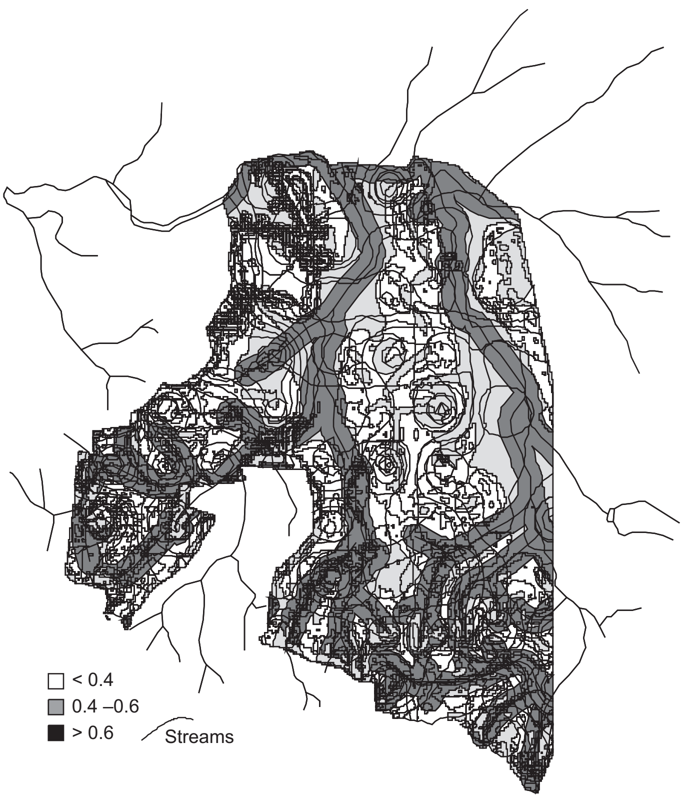

Figure 3. Map of vulnerability showing the MCE solution, including proximity to creeks (40%), slope (40%), erodability (10%) and depth to the restrictive layer (10%). The flat areas close to creeks are more likely to export pollutants due to both proximity to drainage and low slope. Medium slopes with small depths to the restrictive layer are also of high vulnerability (score > 0.6), followed by flat areas of high erodability (score = 0.4–0.6). The lowest vulnerability (score <0.4) is associated with steep slopes located away from the stream network

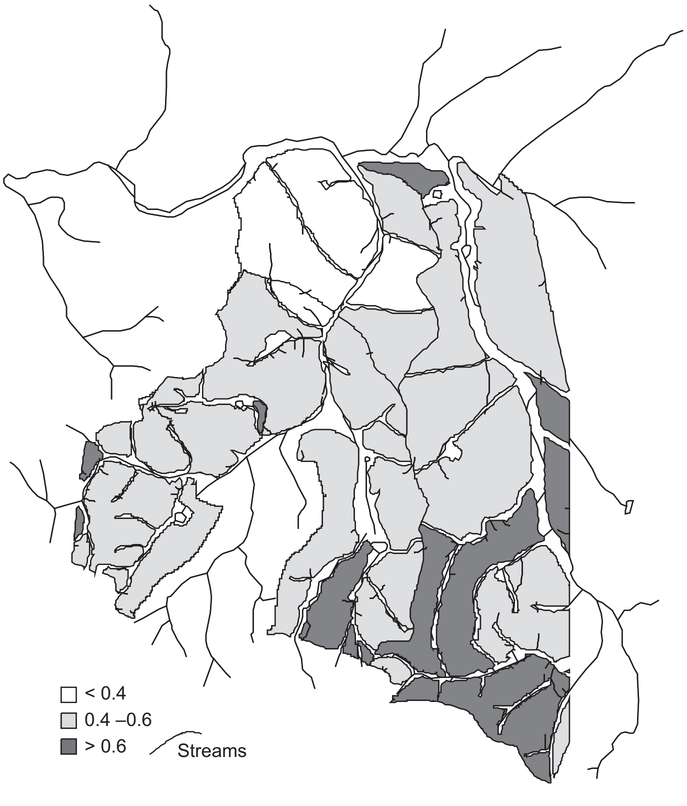

Figure 4. Vulnerability map of weighted scores averaged to compartment level

MCE analysis versus field measurements

The analysis showed that, in addition to areas immediately adjacent to watercourses, the south-eastern corner of this new plantation area is the most vulnerable to waterlogging (Fig. 4). This finding is consistent with field observations.

The application of simazine began on 23 December in the south-eastern compartments (Fig. 5) but it is likely that this had little effect on the water quality of the nearby creeks as there was no rain for 12 days after treatment. However, the 34-mm rain event that followed probably caused the simazine transport and the high 'spike' in the streamwater surface runoff detected on 16 January. Although the treatments continued on 13, 14 and 15 January, the lack of rain at those times and the fact that those compartments are at limited risk (Fig. 4) suggests that the transport of simazine to the stream was also limited. We conclude that the simazine detected at the monitoring site (Fig. 1) on 16 January 2004 was the result of the 34 mm of rain that fell on 5 January and runoff-transported simazine from the south-eastern compartments that were treated on 23 and 24 of December 2003.

A high simazine spike was again detected at the monitoring site on 5 February. It is assumed that this was caused by the 53-mm

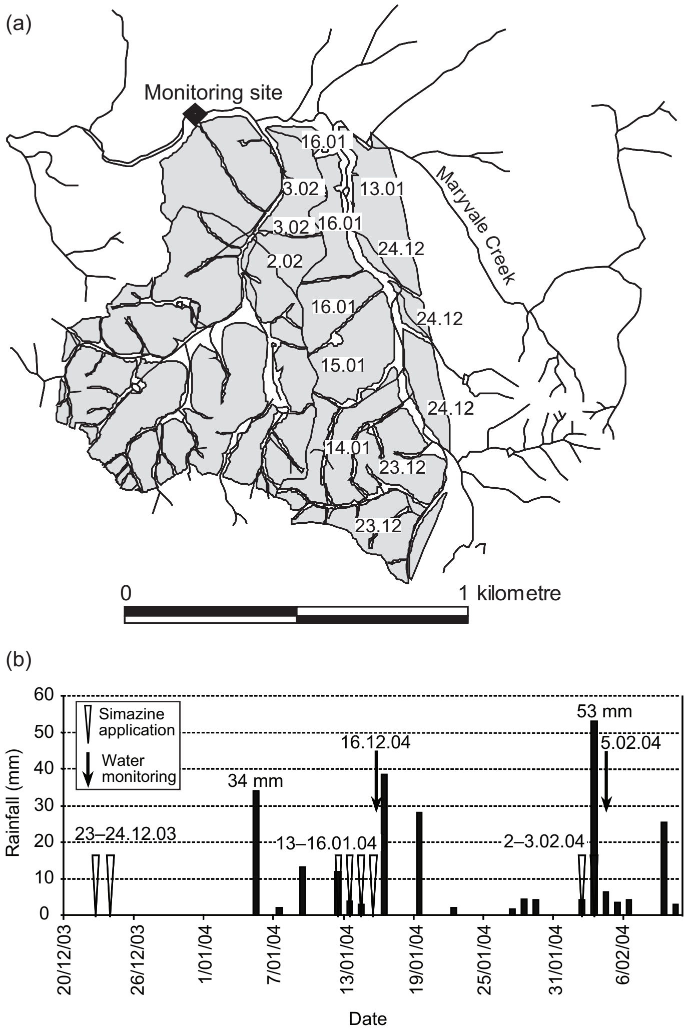

Figure 5. (a) Map of the logging area and (b) diagram showing the dates of simazine application and those of water quality measurements, in relation to rainfall events

rain event that occurred on 3 February, with most contamination being from herbicide recently applied in the northern compartments on 2 and 3 February (Fig. 5). According to the MCE analyses, a significant proportion of the areas around the major watercourse are of high risk, which could explain the high concentration of simazine. However, the February spike was much lower than that in January; this difference is significant when considering that the quantity detected in February was added to that already in the system from the December and January applications. This difference is explained by the MCE, which showed that the compartments treated at the beginning of February were of lower vulnerability than those treated in December.

Case study 2 — Slope stability

Problem description

The subject of the second evaluation was a 120 km^2 *Araucaria* plantation located in subtropical Queensland. As the area assessed is extensive and composed of several state forests, the methodology will be demonstrated using only two logging areas (Fig. 6). The terrain is rugged, of high relief and subject to landslides during heavy rain. Although landslips have been mapped in some areas, a regional GIS-based evaluation of this natural hazard was required.

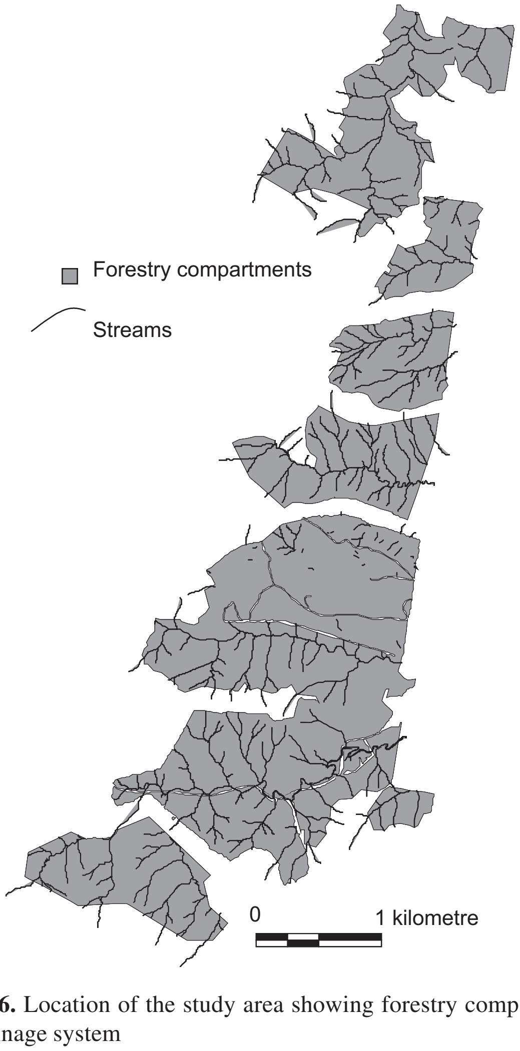

Figure 6. Location of the study area showing forestry compartments and drainage system

Method

Design and rationale

The MCE approach was directed to the assessment of vulnerability to landslides. Considering that the plantation forests had not significantly modified the terrain in the area, the main factors taken into account in this assessment were natural and related to the well-established causes of mass wasting (i.e. landslides), which include:

- adverse bedding or rock structures — exposed bedding or joint planes are surfaces on which rock masses can slide.
- oversteepened slopes — the resisting mass at the base is lessened and potential failure planes, such as stratification, may be exposed; slopes > 25° are the most likely to slide, regardless of the geological material involved.
- increased water content — the water does not necessarily act as a lubricant, but increases pore water pressure and changes the effective stress between mineral grains; in addition, water adds weight to the slope (e.g. Summerfield 1991).

The GIS method used was a multiple-criteria evaluation (MCE) adapted from Carver (1991). The analysis was carried out in a raster format and included the transformation of the vector data into raster format, their reclassification in terms of vulnerability to landsliding, and finally the calculation of the weighted score of vulnerability. The program used was ArcView 8.3.

Parameters and their weights

Based on the theoretical background and considering the available data, the design of the MCE included the drainage system, the slope of the terrain and geological features such as rocks and structures. Several combinations of weightings for different data layers were tested, but the one that best matched the situation in the field was drainage 30%, slope 50%, geology 10% and structure 10%.

As water can be an important control of landslide occurrence, the density of the drainage system in the region was included in the analysis. For the purpose of the analysis, it was considered that the denser the stream network, the more likely is sliding to occur.

Slope was based on the 20-m elevation map of the region. It was considered that slopes > 25° are the most vulnerable to landslides. In addition, on slopes steeper than 35°, tree weight can also decrease stability (Selby 1993).

Geology was based on the 1:100 000 geological map (Natural Resources, Mines and Energy 2004). For the purpose of the analysis, the geological units were ranked into five categories of vulnerability to landslides, from 5 (high) to 1 (low):

- 5 — metamorphic rocks ± sedimentary rocks consisting of schists or other highly foliated rocks
- 4 — sedimentary rocks interbedded with volcanics and unconsolidated alluvium
- 3 — sedimentary rocks including very fine and very coarse material

- 2 — sedimentary rocks, generally sandstones
- 1 — intrusive and volcanic rocks with massive structures (granite, granodiorite, rhyolite, andesite, basalt).

Structure was also based on the 1 : 100 000 geological map. This layer included all known structural features of the area: geological boundaries, various types of faults, lineaments and shear zones, as they all represent weak areas where landslides can be initiated. As with the drainage system, this layer was used to produce a density map, where the denser these features, the more vulnerable the area.

Results and discussion

Vulnerability mapping versus field observations

The intersection of the four layers produced a new raster map (30-m resolution) displaying the vulnerability to landslides (Fig. 7). In general, half of southern section and most of the northern logging area are of concern under wet conditions.

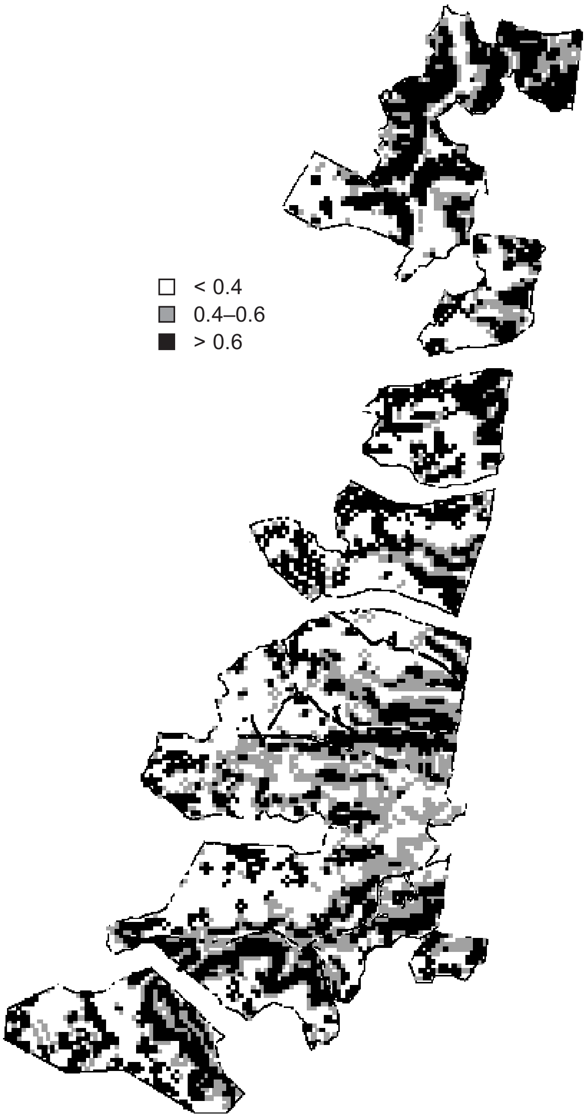

Figure 7. Map of vulnerability to landslides showing the MCE solution, based on the density of the drainage system (30%), slope (50%), geological units (10%) and structural features (10%)

When compared to the situation in the field (Fig. 8), the model appeared to be 'the worst case scenario' because not all the areas highlighted by the vulnerability evaluation were known to experience landslides. This discrepancy may be due to the fact that existing slips are discovered only prior to clearfelling and could be hidden for many decades during the 50-y rotation. Nevertheless, the good correlation between field observations and the desktop analysis revealed new applications for the MCE. Such models are not only predictive (i.e. they identify areas of risk in terms of natural hazards) but also can help the user, while refining the weighting scheme to match the situation in the field, to recognize the main controls over a particular hazard or process. In the case presented here, the MCE version that matched the field situation was slope 50% + drainage 30% + geology 10% + structure 10%; this weighting suggests that topography and the presence of water are the main controls over landslide generation. For other areas where geology is more varied and/or there is a large density of structural features, the weighting scheme would probably need to be changed to accommodate these characteristics.

General conclusions and future work

The multiple-criteria evaluation used in this study has the potential to provide management support by identifying areas vulnerable to pollution or natural hazards. Additionally, it is highly flexible as it can be designed in either vector or raster format, depending on the type of available data.

As the topographical and pedological data used in the first analysis are routinely collected from areas being prepared for plantations, this MCE method can be easily applied elsewhere and also provides a precursor for hydrological modelling. As more field data are collected, the weighting of attributes can be refined to provide an increasingly accurate assessment.

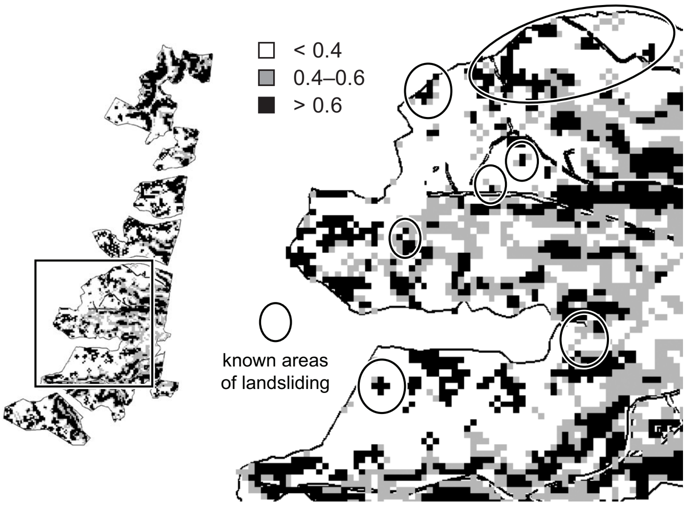

Figure 8. Comparison between the MCE solution and the areas known to have experienced landslides during heavy rain. There is a good correlation between the model and the field observations, although not all the areas considered to be of high risk are known to be hazardous.

The geological and structural data used in the second analysis are currently available for the entire state of Queensland, although the scale or resolution may not always be appropriate for the type of assessment required. However, the most important parameters for many applications are altitude and slope, as these topographic features govern most natural hazards and human-induced processes. As high-resolution digital elevation data become available, more detailed assessments can be obtained.

From the first case study it can be concluded that MCE assessments can be a valuable tool for planning forest treatment, and they should be run before any application of herbicides, nutrients or other soil additives. Supplementary criteria could be added in the analyses. For example, in this study only a buffer zone 100 m wide was applied to the creek layer; additional buffer zones of decreasing risk at greater distances from the creek would produce a more refined assessment. This is especially the case for large areas, where the magnitude of streams should also be incorporated. For example, a region drained by a higher-order stream should have a higher risk associated with it than an area drained by an ephemeral low-order stream.

The second case study shows that natural hazards can be efficiently predicted using the MCE approach. In addition, the comparison of our results with the real situation in the field showed that such models can also help to identify the main controls over a certain process. For example, more field mapping should be directed to the detection of schistose rocks, which are known to create problems in the area. Also important is the determination of the dip of the strata in relation to the slope of the terrain, the monitoring of the water table and the characterisation of the weathering profile, as these elements could help refine the assessment of the local rocks in relation to vulnerability to mass wasting.

In conclusion, the MCE approach offers flexibility in design and shows substantial potential to assist general management by assessing the vulnerability of the forest landscape to either introduced chemicals or natural hazards.

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