A hybrid rule-object spatial modelling tool for catchment analysis

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Abstract

Sustainable land management requires understanding of the cumulative effects of current and likely future land use patterns. A modelling shell (*LAMS*, Land Management Simulator) has been developed to allow exploration of how on- and off-site effects develop in time and space. *LAMS* is tightly integrated with the Arc/Info GIS, and models can freely access spatial data, execute GIS spatial operations and manipulate the spatial display. An application of *LAMS* to land use change in New Zealand erodible hill country is discussed.

Introduction

Sustainable management of productive hill country catchments is a key concern for New Zealand resource management agencies, communities, central government, and industry (Ministry for the Environment, 1996). While there continues to be concern about sustainability of pastoral land use in many hill country areas, there is also a need to ensure that emerging land use patterns provide an appropriate balance between possible detrimental effects, such as reduced water resources, and beneficial effects such as reduced soil erosion.

Resource management agencies and communities need information on land use effects in "large" catchments. Management questions relate not only to the magnitude and timing of effects, but also to priorities for data collection. However, "large" catchments present difficulties in that they are not only physically large compared to small research catchments, but also highly heterogeneous in terms of both the land resources and the processes operating within them. Consequently, predicting the behaviour of such systems represents a challenge for modellers and analysts (Kalma and Sivapalan, 1995).

Although there is a need for greater understanding of the processes operating within catchments, providing practical support for catchment analysis requires appropriate tools for integrating and applying knowledge about spatially distributed systems. Consequently, there is interest in combining knowledge engineering tools with geographic information systems to provide comprehensive spatial modelling technologies for addressing catchment analysis problems (e.g. Mackay *et al.*, 1993; Lam and Swayne, 1993; Reynolds *et al.*, 1996).

Our goal has therefore been to develop tools which support both building and applying process-based and interpretive models for predicting the behaviour of hill country catchment ecosystems. Starting with sedimentation analysis, we have developed a modelling tool (*LAMS*, Land Management Simulator) for investigating catchment land use effects. This paper describes the design of *LAMS* and its application to a lake sedimentation problem associated with pastoral land use in an erodible North Island catchment in New Zealand.

Computer support for catchment analysis

Analysis of land use effects can proceed in three stages

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(Bartell, 1996). In the first stage, the landscape is scanned for the occurrence of risk-generating situations - which will generally be characterised in terms of associations of land use (or management) and land type. Secondly, potential outcomes of these situations need to be formulated, in consultation with the community. Finally the likelihoods of these outcomes must be determined, preferably in terms of risk probabilities.

Society's tolerance of undesirable land management patterns depends on their cumulative effects (Cocklin *et al.*, 1992). Effects may accumulate insidiously over time; they may be the total effect of risk-generating situations upstream or the end result of a cascading sequence of indirect effects; or they may simply consist of a collection of diverse effects. Accordingly a tool for catchment analysis needs to provide facilities to build and link many types of models of varying sophistication, each model reflecting the state of knowledge as well as the availability of data to apply it.

Saarenmaa *et al.* (1994) have shown that decision support and analysis for natural resource management is most effectively provided if the system being modelled can be represented as a set of objects (Coad and Yourdon, 1991) which correspond to real world objects. This "computational framework" provides the foundation for a variety of models, leading ultimately to a library of compatible domain-dependent tools for the particular resource management problem area.

For catchment analysis, the problem of scale has inhibited agreement on the content and structure of such an object model (Kalma and Sivapalan, 1995). Modellers typically have difficulty scaling up from sound understandings of surface and subsurface flow to models which accurately predict the hydrologic behaviour of whole catchments. For example, preferential flow pathways such as tension cracks, fissures or shear zones in unstable hillslopes are usually not considered in hydrologic models based on the differential equations for flow of water in porous media.

Notwithstanding this problem, there are fundamental concepts (or objects) which underpin catchment analysis which addresses sustainability questions (Naiman *et al.*, 1992). For example, catchments comprise subcatchments linked by stream segments. Land within the catchment consists of geomorphological units reflecting surface morphology, regolith type, geology and erosion processes. Soil classes and properties can be inferred from geomorphology using soil-landscape models. The "representative elementary area" and "hydrological response unit" are similar discrete area concepts used to model catchment hydrology (Wood *et al.*, 1988, Flugel, 1995). Further, sediment and nutrient loadings of surface and subsurface water, and the chemical transformations of the solutes, are determined by the ways in which flow pathways intersect with these soil or geomorphological units.

These and other concepts (including those which underpin modelling of socio-economic factors) potentially provide the basis for an object-oriented, spatio-temporal catchment modelling tool which can be used at a variety of scales. Because of the clarity and ease of explanation of simple rule-based interpretive models, and because resource management scientists who are not programmers need easily accessible modelling aids, rule-based knowledge representation is also required (Carrico *et al.*, 1989). Essential requirements of such a modelling tool are that it should be easy to modify and extend models to reflect the issues of concern to different communities, and that the tool provides efficient access to spatial data in a form which is easily maintained and verified.

LAMS modelling framework

Overview

The essential components of the Land Management Simulator catchment analysis system, similar in concept to that described by Fedra (1995), are shown in Figure 1. The system contains database, modelling and geographic information system components which can be accessed via graphic development and application interfaces. A core feature is a simulation manager which evolves land use and land cover patterns through time, and applies models to predict effects and changes in risk levels. *LAMS* uses both object-

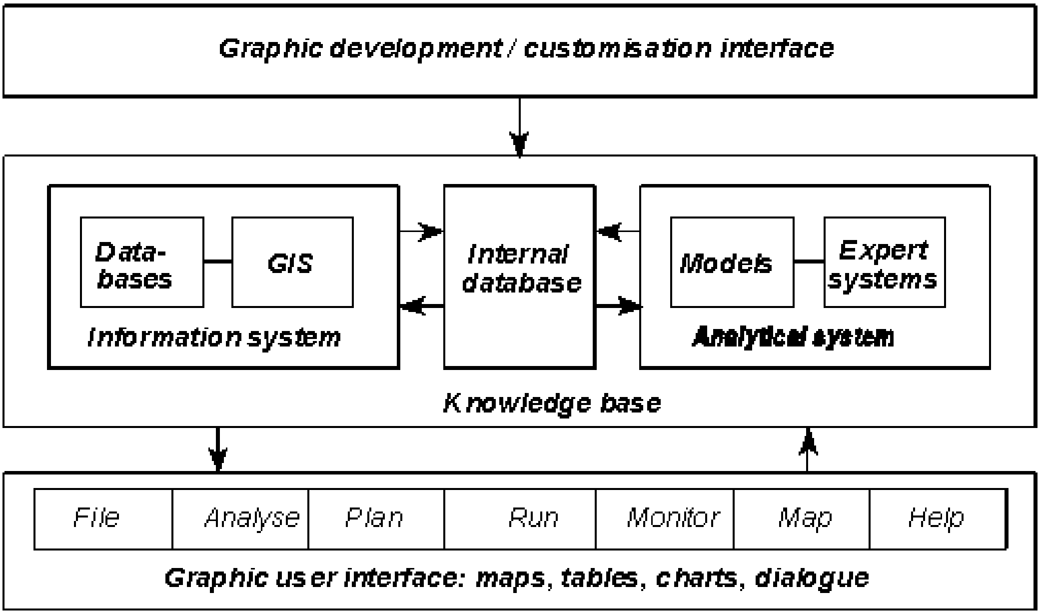

Figure 1 Architecture of the catchment modelling and analysis system

oriented and rule-based knowledge representation techniques.

LAMS has been developed on a Sun workstation. We have used the Smart Elements knowledge-based development environment from Neuron Data in combination with ESRI's Arc/Info geographic information system. Smart Elements integrates a hybrid rule / object-oriented expert system shell (Nexpert *Object)* and Open Interface, a cross-platform Graphical User Interface (GUI) developer (which may assist development of a PC version of *LAMS*). Overall control and model management are handled within Nexpert *Object.* The ease with which the flow of control and the hierarchy of data structures can be viewed within Nexpert facilitates understanding. Some simulation modelling is coded directly in C, for greater efficiency. The GUI development features of Smart Elements have been used to construct an interface (Figure 2) involving data entry and output screens in the form of editors, a network browser, charting and mapping capabilities and textual reports. Most GUI development has been coded in C, although Smart Elements provides scripting support for some GUI elements. *LAMS* can read from and write to ARC/INFO databases through a set of C routines, and can control the GIS through commands issued through an Inter-Application Communication (IAC) connection (ESRI, 1995).

Representing the spatial domain

We model the stream channel network within the catchment as a set of stream segments or reaches. Each of these is an object, inheriting attributes and operations from the stream segment class. A small number of local subcatchments (LSCs), the smallest catchment unit represented, drain into each stream segment. These local subcatchments may provide point or linear water sources to the stream segments, depending on whether they are defined around particular streams or whether they simply drain into the stream segment over part or all of its length. The total catchment for a stream segment is then the collection of LSCs for the segment and all upstream segments.

The fundamental modelling unit is the land response unit or LRU, similar in concept to both the landscape response unit in landscape ecology (Perez-Trejo, 1993), and the hydrological response unit (Flugel, 1995). We define contiguous areas of land with a common manager as socio-eco-

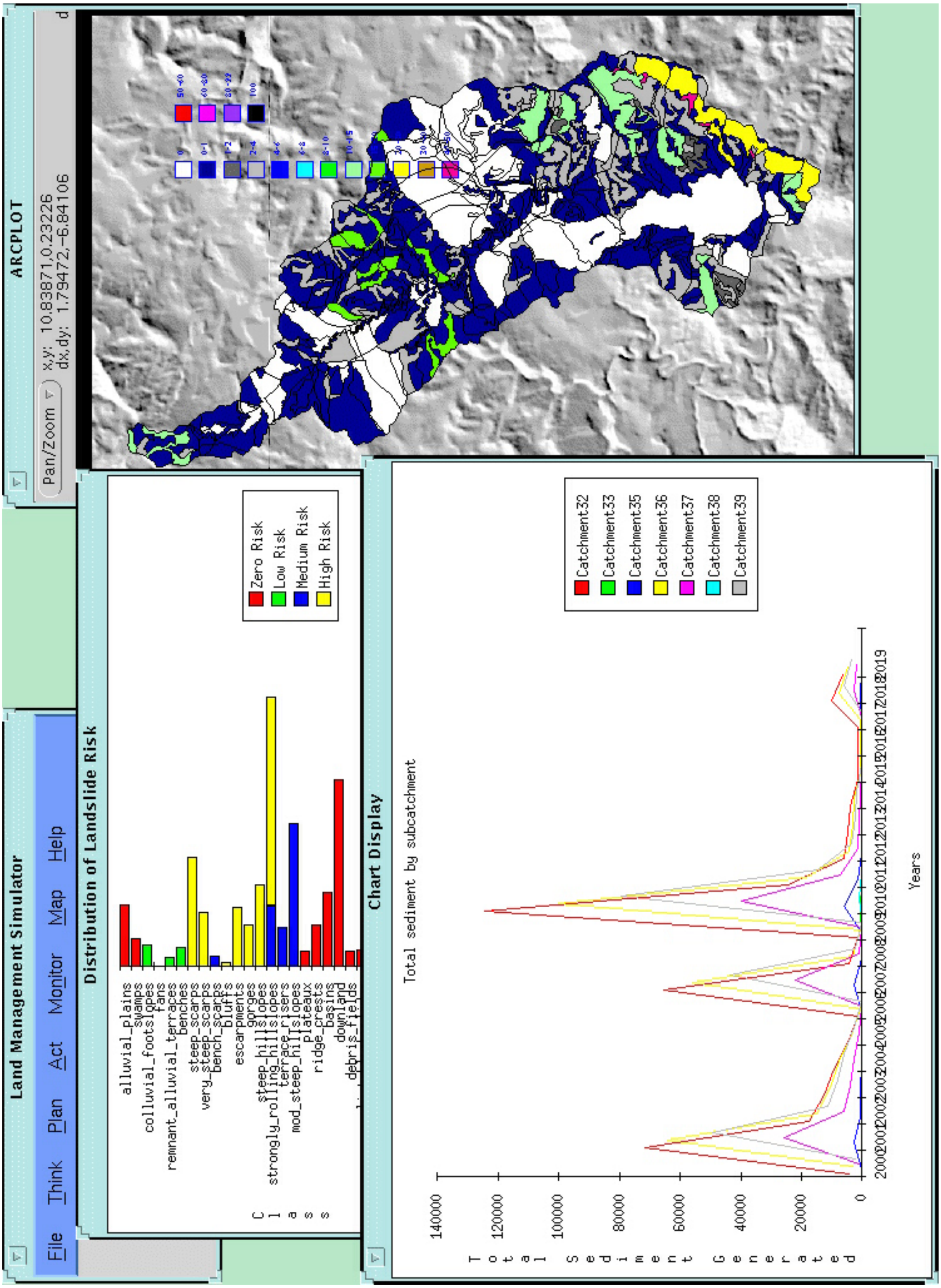

Figure 2 The Land Management Simulator graphic user interface.

nomic units (SEUs), and describe the terrain through a set of geomorphic land classes (GLCs), which are available as mapped polygons or as a non-aggregated classified raster image. We then define an LRU as a conceptual unit comprising all land within a given LSC and SEU which belongs to the same GLC. Land management may vary within the LRU - which is modelled as a set of land use (or management) units (LUUs) (Figure 3). The resulting class-object hierarchy for the catchment ecosystem is represented in Figure 4, following the notation of Coad and Yourdon (1991). The object model facilitates rule-based reasoning about the system or selected parts of it, while direct representation of connectivity and parent-component relationships, in addition to classifications, supports routing of messages to appropriate objects.

Land use and vegetation change

Changes in land use are modelled using land use transition rules. These rules specify when and where land use change will occur, and the nature of the land use transition. The rules are currently deterministic, but could be stochastic, reflecting specified levels of uncertainty about land manager decisions or changes in land ownership (Dale *et al.*, 1993, Lee *et al.,* 1992). Data describing spatial and non-spatial pre-conditions for change, and the changes which occur, are captured on an editor screen. Each transition rule is attached as a method to an object in a class of "land use change rules".

The condition lists of rules take into account the terrain class (GLC), the position in the catchment (subcatchment or local subcatchment), the ownership, and the existing land use. Factors which motivate the land use change are treated implicitly with this representation. More complex rules which consider factors such as the state of neighbouring properties, economic indicators, or whether there has recently been a major erosion event, can be created using the graphic expert system development interface directly. Collectively, groups of land use transition rules specify land use scenarios.

Changes in land cover also occur as a result of maturing vegetation or natural succession. We employ the concept of a vegetation phase; land not in productive use follows different succession patterns (sequences of phases) under different conditions. We associate a phase sequence or succession model with each area which is removed from productive use. Each phase and its associated attributes is represented as an object within a class of vegetation phases. Each land response unit has an attribute describing the anticipated sequence and timing of phases, in case parts of the LRU are withdrawn from productive use, or already contain areas of scrub or regenerating indigenous vegetation. Succession models are allocated interactively to spatially-defined classes of LRU's.

Application to sedimentation analysis

Many environments in New Zealand are susceptible to

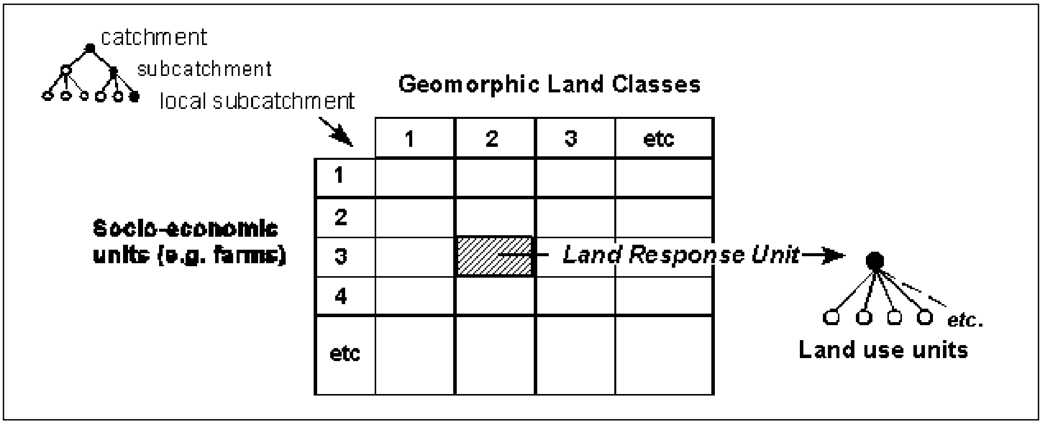

Figure 3 Basic modelling units employed in the catchment modelling analysis system.

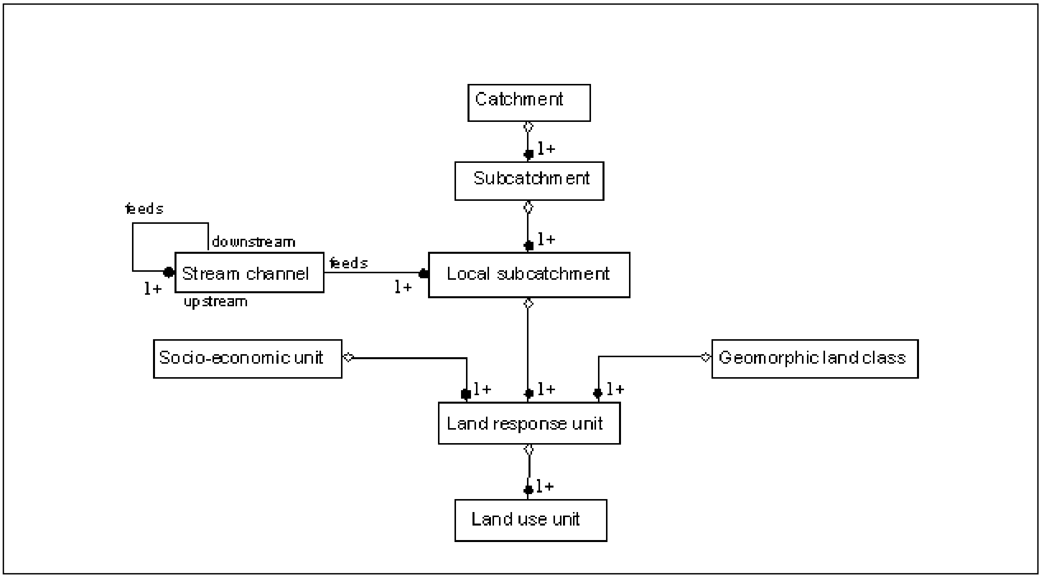

Figure 4 Class hierarchy for representing spatial and conceptual relationships within catchment

soil erosion. The resulting sedimentation can lead to flooding, loss of habitat, and reduced water quality. One example is the 32 km^2 Lake Tutira catchment in northern Hawkes Bay (Trustrum and Page, 1992). There, resource managers are interested in how land use change within the catchment will affect lake sedimentation which has proceeded at high rates since clearance of indigenous vegetation (Page *et al.,* 1994a). Resource managers have also expressed interest in the possibility of designing land use changes so that the catchment can withstand rainstorms of a specified magnitude or frequency without causing significant lake sedimentation.

The approach we have adopted is to simulate, on a yearly basis, the projected changes in land use or land management within the catchment, and use (at this prototype stage) very simple empirical models to suggest possible effects. In future, we anticipate elaborating these models and incorporating interpretive models to test for significance of effects and to explore indirect effects.

The catchment is subjected to a sequence of annual maximum rainstorm events, which are either specified by the user or selected randomly from an extreme value distribution. A linear empirical response model is used to compute the amount of landsliding on susceptible slopes (where slopes and rainfall exceed empirically-determined thresholds), assuming pastoral land use under "standard" management. The amount of erosion is then adjusted empirically to take account of factors such as land management, land cover, age of trees, and the available soil resource.

Chronic erosion and sedimentation delivery to streams is modelled as empirically assessed annual transfers between landform components (Reid and Trustrum, *in prep*). For each land use unit (LUU), erosion processes and sediment transfer rates for pastoral land use are inherited directly from GLCs (Figure 5). LUUs inherit methods from land use classes which allow these rates to be adjusted for the nature of the land cover.

Risk quantification requires determining the probability, following a storm of given magnitude, that more than *x* mm of sediment accumulates in Lake Tutira. Our approach is firstly to assess the probability under the current land use regime. While for other sedimentation problems this "current risk" might be assessed differently, for Lake Tutira we were able to use an empirical log-linear relationship between storm rainfall and the thickness of sediment deposited in the lake, obtained by an analysis of lake cores

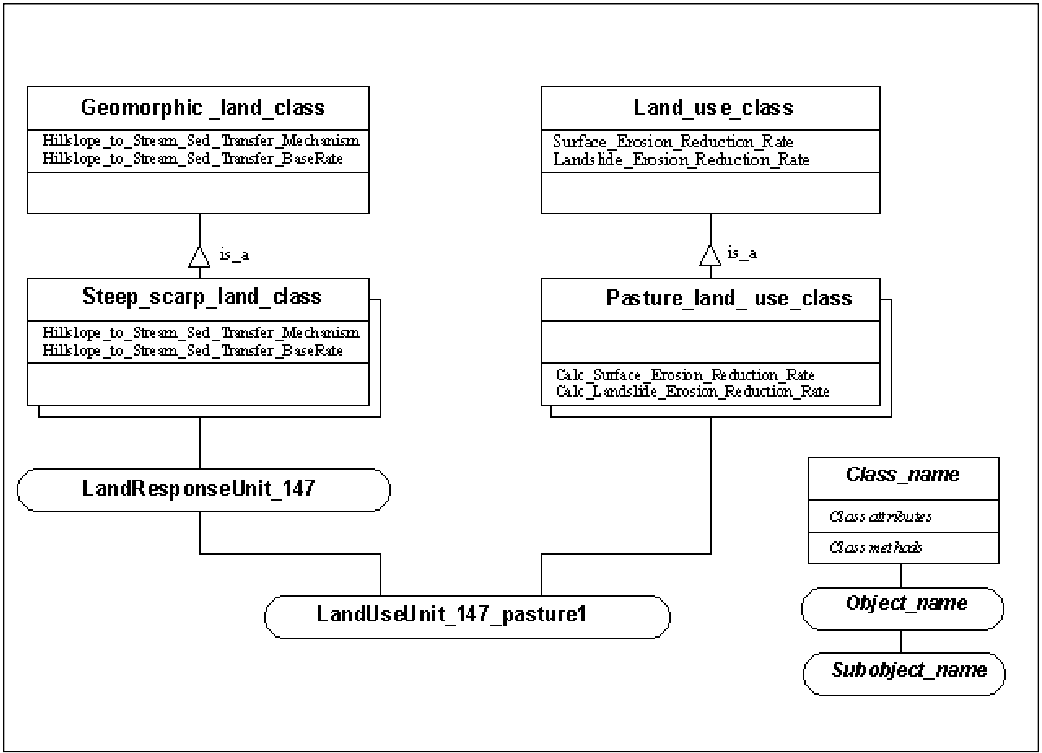

Figure 5 Inheritance of methods and attributes for computation of land use-adjusted sediment transfers.

(Page *et al*., 1994a). We then revise this probability, taking into account the likely effects of changes in land management on erosion and sedimentation processes.

To determine the effect of land use on sedimentation we first establish the major processes by which sediment is generated (by erosion or remobilisation of sediment in temporary storage) and reaches the lake, for the storm rainfall in question. For this we employ expert-derived curves giving bounds on the contribution of different erosion processes to the total volume of sediment reaching the lake, as a function of storm rainfall. A sediment budget for Lake Tutira catchment has been evaluated by Page *et al*. (1994b). Landsliding contributes most of the sediment for the large rainfall events, but the bounds are further apart for the smaller events for which processes such as streambank erosion and channel erosion can become significant.

During simulation of land use change we "monitor" the change in state of key sediment sources. Having identified the principal mechanisms responsible for the sediment delivered to the lake for a rainstorm of the size in question, for current conditions, we search the areas of land use change upstream to establish the list of land use units subject to these processes. We then determine the extent to which vulnerability to the contributing mechanism has been affected by land use change. The (increased or decreased) percentage change is computed by applying empirical factors deduced from available land use impact information. Depending on the mechanism under consideration, this requires separate evaluation of a range of factors which can affect sediment delivery. While we have not made use of hydrological models to date, we envisage these will be useful when we attempt a more rigorous analysis of the effects of land use on sediment delivery. For example, resolving whether factors such as changes to peak flows and rainfall interception rates could significantly affect the importance of individual sediment supply mechanisms can become the focus for separate knowledge-bases.

To establish the impact of land use change on landslide erosion, we firstly search for landslide-prone areas which have undergone land use change. Where land use has changed to forestry, the land's new vulnerability to landsliding at each location is computed from the age of the trees, and from the time which has lapsed since the end of the previous harvest cycle, after the first rotation. For areas which are undergoing succession-driven changes in vegetation cover, changed vulnerability to landsliding depends on landslide-inhibiting characteristics of the land cover which are stored with the vegetation phase objects.

Worst case and best case scenarios for sediment generation are constructed using a linear programming algorithm (Winston, 1991) which determines bounds on the change in sediment delivery. Worst cases occur when the sediment sources which would be most affected by the land use change contribute the least to the sediment reaching the lake. An appropriate weighting of worst and best case reductions (e.g. the average reduction) in sediment delivery caused is used to compute a revised risk probability which is classified using simple rules. The user can then run the model for a number of years and determine when sedimentation risk becomes acceptable.

The overall logic of this analysis is represented using rules to help make it more visible (through the rule network viewer) and easily understood. Evaluating conditions and performing actions associated with these rules involves computation, queries to the internal (object) database, and further rule-based inference. The rule-set achieves spatial reasoning though queries which exploit knowledge of the upstream-downstream relationships made explicit in the catchment representation.

Conclusion

The goal of this research has been to develop and apply an object-oriented framework to support analysis of land use effects in hill country catchments. We have developed an object-oriented data model which now forms the basis for the *LAMS* catchment modelling tool. This tool, which has been built by tightly linking knowledge engineering and geographic information systems components, has been successfully applied to analysis of lake sedimentation risk. Both the underlying object model and the modelling approach used for sedimentation analysis have potential for application to problems relating to catchment hydrology, stream water quality, or to valued environmental components such as spawning grounds for fish. In future we anticipate using and further testing the *LAMS* conceptual model by developing knowledge-bases and models to address a variety of catchment management issues.

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