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A framework for modelling erosion and sediment transport in a large drainage basin

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Abstract The modelling framework proposed here consists of two major components: an upland catchment model and an in-stream model. The upland model simulates streamflow (*Q*), suspended sediment (*SS*) and associated phosphorus (P) using rainfall data, and is calibrated to daily streamflow time series under historic conditions. The in-stream model routes *Q*, *SS* and P from the outlet of upland catchments or in-stream nodes to nodes downstream. The upland conceptual rainfall–runoff model is parametrically efficient and very effective in predicting streamflow. The in-stream transport model can infer sources (resuspension and bank erosion) and sinks (settling) within a reach. Air photographs are used to assess the on-site effects of climate and land cover/use on erosion and the drainage network. Changes in land cover/use and the effects on the drainage network are related to the parameters in the rainfall–runoff model so that associated effects on *Q* (and hence *SS* and P) can be assessed. This modelling framework is prototyped on the Namoi basin in northern New South Wales, Australia.

INTRODUCTION

The on-going degradation of the earth's land and freshwater resources resulting from natural and human pressures is a sustainability problem of the highest priority. Effective management of this degradation requires addressing its social, economic, political, institutional and natural science dimensions (United Nations Conference on Environment and Development, 1992). A framework, which facilitates an appreciation of the local and cascading effects of land and water use options in a catchment system, may provide an essential contribution to improving resource management in being more sustainable, equitable and efficient. In this paper the development of such a modelling framework is illustrated in terms of the physical effects, with potential extension to consider biological, social and economic effects (Jakeman *et al.*, 1997).

Definition of the physical problem

The problem being addressed here can be stated as follows:

(a) to infer the on-site (~1–10 km^2) and integral off-site (~10^2–10^4 km^2) effects of variations in climate, landscape attributes and land-use/management in terms of erosion, water supply, and water quality (e.g. suspended sediment and nutrient concentrations);

(b) to separate the effects of climatic forcing from the effects of landscape and land use/management;

(c) to identify the relative contribution of different land (and water) areas to downstream effects, both historical and potential as these will vary with climate and land-use activities.

The scales specified in (a) are regarded as the minimum ones that can be justified by the information content in the data available, yet are still useful for management purposes. Spatial data on erosion and the size of land units allowing satisfactory analysis dictate the scale of erosion effects. The streamgauge network dictates the scale of prediction of upland water quality effects.

The difficulty of the problem

The environmental modelling problem defined above is characterized by:

(a) *Natural complexity:* Flows of water, sediment and nutrients, between and within media; each possess their own dimensions, time constants, spatial scales, through-puts and thresholds.

(b) *Spatial heterogeneity:* The media (the atmosphere, land surface, subsurface, streams etc.) are not uniform, and some transport processes may be non-conservative (e.g. involving deposition, resuspension).

(c) *Sparse measurements:* System information will be disparate, spatially unrepresentative and generally error-laden, with limited observations of many internal system processes.

In the spirit of Clark (1986), we do not model such a problem in order to come up with a very detailed set of predictions. The combination of system complexity with data and model uncertainty make such prediction infeasible. Instead, we seek to build a framework and models to characterize the physical system, providing a basis for assessing how to intervene and influence desired land and water quality outcomes more to society's benefit.

Properties of the modelling framework

A modelling framework to treat this issue should possess the following properties:

(a) comprise a set of generic models, one for each subsystem type (e.g. rainfall–runoff, and in-stream flow), which allows investigation of the spatio-temporal system effects of climate forcing, landscape and land use;

(b) incorporate knowledge of the key processes in the catchment system;

(c) be consistent in conceptual complexity and discretization interval with the information content in the databases available;

(d) link spatially-distributed generic model components for simulation of cumulative effects at desired locations in the catchment network.

A central issue determining the precise prescription of the modelling framework is the database. In order to sharpen some of the foregoing discussion, the relevant database that is available for modelling runoff, erosion, sediment and nutrient concentrations in the Namoi basin, New South Wales, Australia, is described in the next section.

ASSESSMENT DATABASE: NAMOI BASIN

Description of the Namoi basin

The Namoi basin (42 000 km^2) is located within the Murray–Darling basin in northern New South Wales (see Fig. 1). Mean annual rainfall varies from 470 mm at Walgett in the west to 1100 mm at the top of the Great Dividing Range in the southeast. Rainfall is summer dominant, characterized by high intensity, short duration thunderstorms which can result in flooding and significant erosion.

The catchment lies within a region of complex geology. A major structural lineament trending north-northwest, the Hunter-Mooki Thrust System, bisects the region from the catchment boundary south of Nundle to Warialda in the north. To

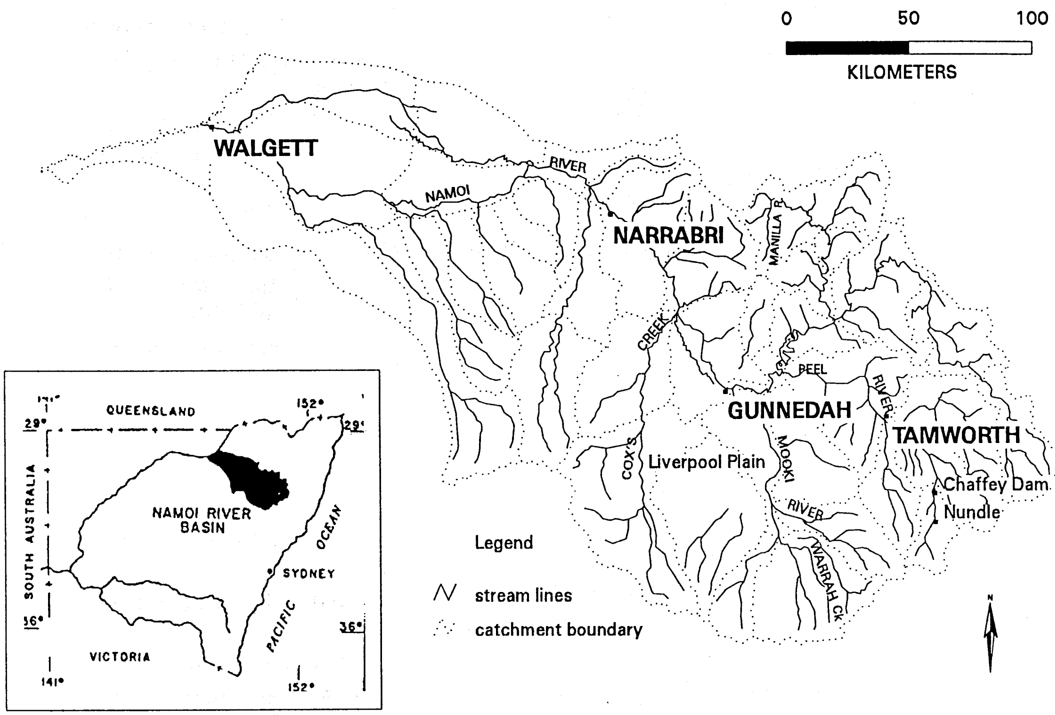

Fig. 1 Location of the Namoi basin.

the east of this fault zone, the basement rocks comprise tightly folded and intensely fractured Ordovician and Silurian meta-sediments and limestones overlain by a succession of Late Devonian to Carboniferous sediments. These rocks are intruded by the New England Granitic Batholith from the north of Tamworth to the Queensland border. The Gunnedah and Oxley-Surat basins lie to the west of the fault zone, and are separated by the Jurassic Garrawilla Volcanics. Overlying these rocks are gently dipping successions of sediments which include shale and economic coal seams. The youngest consolidated rocks of the catchment are the Cenozoic volcanics which outcrop extensively and define the Nandewar Ranges, Liverpool Ranges and the Warrumbungles. Weathering and erosion of these basic volcanics has produced the highly fertile alluvium of the Liverpool Plains in the vicinity of Gunnedah (Fig. 1).

The Namoi basin is a productive agricultural area supporting beef and sheep grazing, and both dryland and irrigated cropping. Dominant winter crops include wheat and barley, and the dominant summer crops are sorghum, sunflowers and cotton. Intensive land use includes dairying, cattle feedlots, piggeries and poultry farming. Approximately half of the catchment supports grazing, and one quarter of the catchment is used for cropping.

Climate and stream network

Precipitation and streamflow databases, which are necessary for inferring water availability and quality, are only available over scales of >100 km^2 and vary considerably in representativeness and accuracy. Figure 2 shows the precipitation

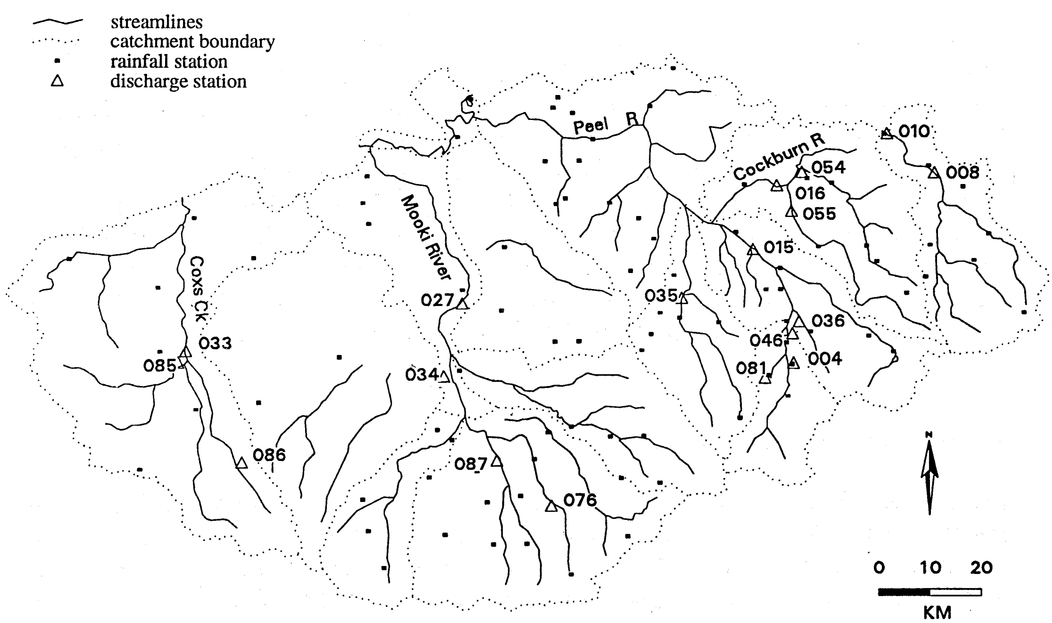

Fig. 2 The precipitation–discharge measurement network for the southern uplands of the Namoi basin.

and discharge measurement network for the Cox's Creek, Mooki, Peel and Cockburn River tributaries of the Namoi River. The first two flow from the Liverpool Ranges and Plains. There are only two catchments under 200 km^2 with measured streamflow, and their record length varies from 11 to 21 years. The density of concurrent raingauge stations in these smallest streamgauged catchments ranges from 93 to 150 km^2 per gauge.

Hansen *et al.* (1996) have studied eight catchments in the Clarence basin to the northeast to examine the predictive accuracy of a daily rainfall–runoff model. The streamgauge rating and raingauge density were principal factors in the level of accuracy achieved. Duncan *et al.* (1993) found that raingauge density has a very strong effect on the accuracy of hydrograph parameters, with the standard error falling off as a power law with increasing gauge density.

Stream-water quality measurements

The area shown in Fig. 2 contains the highest frequency water quality measurements in the basin. There are nine stations sampling water continuously and six of these have been in place since 1995. In addition to the above, there are five sites at which monthly grab samples are taken and six monitoring sites where weekly to fortnightly samples are taken. The authors have also instigated event sampling (~8 hourly) by landholders at five locations.

Landscape spatial data

Since the 1940s air photographs have been taken at approximately decadal frequency. These photographs have been used by Beavis *et al.* (1997) to map land cover, streamlines, gullies and rills in the Cox's Creek catchment above Tambar Springs (gauge 033 in Fig. 2) and in the Warrah Creek catchment (gauge 076). The maps have been digitized to estimate changes in gully and rill erosion through time and space in relation to land cover, climatic influences, soil and geological substrate.

Erosion and land cover data in the basin have been digitized for the 1980s. Land cover data, produced by satellite imagery, have recently been constructed by the NSW Department of Land and Water Conservation in the Liverpool Plains catchments for the summer of 1996/97 and the winter of 1997.

Sediment tracer measurements

Field observations of soils and sediments and analysis of natural environmental tracers in soil and water samples can be used to infer the genesis and, in some cases, the age of material in the basin network. For example, caesium and lead isotopes can help differentiate between topsoil and subsoil contributions (Olley *et al.*, 1996). Optical scanning luminescence can date the deposition of phosphorus in a sediment profile.

GUIDELINES FOR MODELLING FRAMEWORK

In constructing a modelling framework to address the problem defined above, the following guidelines were used:

- Identify those system states and outputs which can be predicted with existing data, information and knowledge (and their spatio-temporal scales).
- Construct models of subsystem components wherein parameters and other unknowns to be inferred reflect subsystem response properties/characteristics.
- Relate characteristics to measurable subsystem properties (this may require a systematic data collection and causal analysis of each subsystem type in other locations where the requisite data can be acquired).
- Use empirical information for determining those outputs or states which cannot be modelled conceptually or physically.

THE UPLAND MODELLING COMPONENT

Given the above guidelines and the databases and model types available, the upland component of our modelling framework for predicting the on-site and spatially cumulative off-site effects of sediment and nutrient loss is presented below. Figure 3 summarizes the framework.

Rainfall–runoff model

The conceptual rainfall–runoff model IHACRES (Jakeman *et al.*, 1990; Jakeman & Hornberger, 1993) is used to generate daily streamflow from rainfall and temperature inputs. Like most conceptual rainfall–runoff models, it can predict streamflow with catchment-scale observations of precipitation and streamflow only. It has several

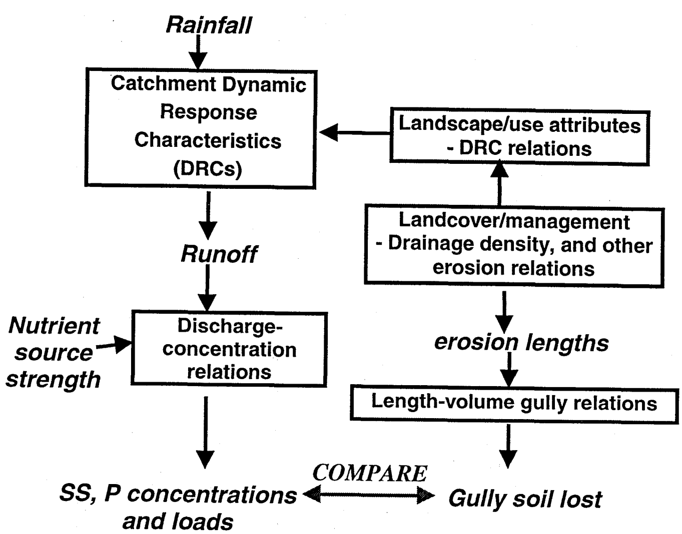

Fig. 3 Modelling framework for upland catchments.

advantages, most of which are not shared with other conceptual models, viz.:

(a) It predicts runoff well across a wide range of hydroclimatologies, especially in its most recent forms with updated evaporative loss modules (Ye *et al.*, 1997).

(b) It is highly efficient (five–seven parameters) and therefore can be estimated from relatively short periods of record (a few years of daily precipitation and discharge).

(c) The parameterization encapsulates the response dynamics of catchment-scale behaviour allowing a characterization of similarities and differences in response between catchments (Jakeman & Hornberger, 1993).

(d) The encapsulated model dynamics, which are derived easily from the model parameters, have been called dynamic response characteristics (DRCs) because their values are largely independent of climate in the model estimation/calibration period (Jakeman *et al.,* 1993).

(e) DRCs can be related to landscape attributes, e.g. quickflow recession rate corresponds to drainage density (Post & Jakeman, 1996); potential catchment moisture storage is influenced strongly by vegetation cover (Post, 1996).

(f) The DRC known as the quick flow hydrograph peak (the quickflow response to a standardized pulse of rain) has been illustrated to relate well to long-term mean and 90-percentile turbidity in the Murrumbidgee River (Post, 1996).

Discharge–concentration relationships

Relationships which allow material concentrations like suspended sediment and phosphorus to be derived from discharge are determined from the data. Various options exist to derive these relationships. One is to use or recalibrate a long-term relation between quickflow hydrograph peak and turbidity or suspended sediment routinely on an event basis. A second option is to relate cumulative material load to cumulative discharge through a power law. This has worked well (Barnes *et al.,* 1997; Crapper & Barnes, 1997) and has the advantage that the exponent in the power law relates to position in the landscape so that it might be possible to infer an exponent value at locations between concentration measurement sites, especially where discharge is recorded.

Spatio-temporal landscape analysis

The aim of this analysis from air photographs is to assess the effects of climate, land cover and land management on rill and gully erosion and the drainage network. The analysis is being used to produce a set of rules which state how climate, land cover and management affect on-site erosion and the drainage network. The predictive relationships between landscape attributes (e.g. drainage density or land cover) and dynamic response characteristics (e.g. quick-flow hydrograph peak or runoff ratio), estimated by the rainfall–runoff modelling exercises, can then be used to modify the IHACRES model parameters.

Comparison through time in the same subcatchment controls for geology, slope and sometimes land cover and management, thereby allowing the effect of climate preceding the photographic period to be examined. Once the effect of climate has been determined, temporal comparisons can be made within individual subcatchments identified to have changes in land management (such as contour banking) and then land cover (such as native pasture/woodland versus intensive pasture or cropping).

Comparison across catchments between the same time slices controls for climate to some extent. So, for example, changes in erosion over the same 10 and 20 year periods have been quantified for subcatchments with similar geology, soils and slopes. The outputs of runoff and material concentration can then be simulated at all upland catchment sites for historic and hypothetical climate and land use. These are then inputs to the in-stream process model.

IN-STREAM MODELLING COMPONENT

The in-stream modelling component has a generic model linked to a landscape (stream morphology and riverine vegetation environment) classification and analysis, in this case to identify sources and sinks of sediment in reaches (see Fig. 4).

In-stream model

The model described in Dietrich & Jakeman (1997) has been developed from that in Dietrich *et al.* (1989) to aid identification of the sources and sinks of sediment within reaches (Green *et al.*, 1997), and to route material through the reaches of a stream network. The major features are mass conservation, advection, and settling and resuspension mechanisms. It is a conceptual model which makes certain necessary assumptions so that the parameters associated with mechanisms can be estimated more reliably from upstream–downstream concentration measurements. For example, for sediment, there is a resuspension threshold velocity function which is a power law when flow rate is above a critical value and zero otherwise.

Stream bank erosion monitoring

Bank erosion sites are being monitored for a range of parent materials, stream size and power, and channel morphology. Each site was selected where bank recession

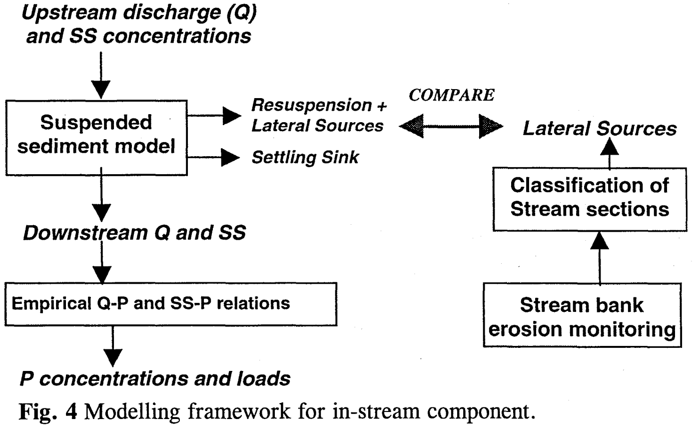

Fig. 4 Modelling framework for in-stream component.

was active on the outside of a bend, relatively straight but widening channel section, or upstream portion of the inside of a bend. Changes in stream-reach and bank morphology over decadal times are being assessed using air photo analyses. Bank erosion sites similar to those being monitored are interpreted, and within each stream reach a spatial frequency distribution is assigned to each type of bank erosion monitored. Thus, an upper bound is estimated for sources of sediment from banks for given seasons and flow regimes (local re-deposition is neglected).

For more precise quantification of the large-scale average bank erosion, the difference in suspended solid loads between upstream and downstream stations is related to a source term in the calibrated transport model, which in turn is related to bank erosion (Green *et al.*, 1997). The transport model makes it possible to quantify a mass of material from bank erosion, thereby allowing us to compare this with estimates derived from our spatial and temporal functional relationships between stream morphology (from air photo analyses) and measured bank erosion.

STRENGTHS AND LIMITATIONS OF THE FRAMEWORK

The framework presented here is largely a conceptual one, dosed appropriately with empiricism. It is sufficiently management-oriented to be able to provide useful indications of the on-site and off-site effects of climate and land use, but not so empirical as to unduly limit its ability to evaluate management options.

The advantages of this approach are that: it is temporally continuous and the time step can be selected short enough for the model to be event responsive; it attempts to separate climate, landscape and land use effects; it deals with gully and stream-bank erosion as the predominant sources of sediment, but can be combined with sheet and rill erosion models; assesses on-site (erosion) and off-site (water quality) effects; it is based on an intermediate scale (on the order of 100 km^2) for validation, but allows sub-scale variations in land cover/use to affect parameters at the intermediate scale, and uses routing to obtain discharge, *SS* and P concentrations at larger scales (avoiding the scaling up problem of a plot-scale approach); and it is anchored to field measurements.

The whole methodology is data-driven, the perceived weakness being that it cannot be applied immediately to other cases. However, any method will, in practice, require data to infer model parameter values. The model structures in our approach are very transportable to other locations, and do not demand an unreasonable monitoring investment.

The modelling procedure is computationally inexpensive, especially in "what-if" mode. That is, once the parameters are estimated, simulation of climate and land use options is virtually instantaneous. The model components are easily updatable so that parameters and relationships can be refined as more information and data come to hand. Improvements to the approach will come from better understanding of upland and in-stream nutrient source strengths.

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