A Modelling Framework for Erosion, Sediment and Nutrient Transport from Catchment to Basin Scale

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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 produces discharge (Q), suspended sediment (SS) and associated phosphorus (P) from rainfall, and is initially calibrated from daily rainfall-discharge 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 component is centred on a conceptual rainfall-runoff model which encapsulates catchment response in a parametrically efficient manner and which has high effectiveness in predicting discharge. The in-stream component is an advective model which can also infer sources (resuspension) and sinks (settling) versus Q within a reach. Empirical relationships developed from observational records are used to determine SS and P from Q at a station nodes. Spatio-temporal analysis of air photographs is 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. Reaches are classified into stream section types and each type is being monitored for bank erosion versus discharge. The combined erosion in each reach informs the in-stream model about the values of its source term.

The advantages of the modelling approach are that it: is temporally continuous and the time step can be selected short enough for the model to be event responsive; attempts to separate climate, landscape and land use effects; assumes and deals with gully erosion as the predominant source of sediment but can be combined with sheet and rill erosion models such as those based on the Universal Soil Loss Equation; assesses on-site (erosion) and off-site (water quality) effects; 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 is anchored to field measurements. This modelling framework is prototyped on the Namoi Basin in northern New South Wales, Australia.

Improvements would come from: a better understanding of nutrient source strengths and types, and the relationship of P to suspended sediment (upland and in-stream) concentrations; further identification in other landscapes of landuse effects on erosion; and longer-term monitoring of SS and P.

1. 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 (UNCED, 1992).

An essential contribution that can be made to assist resource utilization in being more sustainable, equitable and efficient is a framework which facilitates an appreciation of the local and cascading effects of land and water use options in a catchment system. 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).

1.1 Definition of the Physical Problem

The problem being addressed here can be stated as follows:

(i) to infer the on-site (~1-10km^2) and integral off-site (~10^2-10^4 km^2) effects of variations in climate, landscape attributes and landuse/management in terms of erosion, water supply, and water quality (e.g. suspended sediment and nutrient concentrations)
(ii) to separate the effects of climatic forcing from the effects of landscape and land use/management
(iii) 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.

Components (ii) and (iii) are actually included in (i) but deserve individual specification. This is because, in the case of (ii), it needs to be recognized more widely that clarification of the combined role of climate with different land uses can only inform the management process. In the case of (iii), an historical appreciation of the relative contribution of different parts of a catchment system is necessary to build up our knowledge base of cause and effect relationships but it must be assessed how these contributions may vary over time with climate or other land management options.

The scales specified in (i) 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 (see section 2.4) and the size of land units allowing satisfactory analysis dictate the scale of erosion effects. The stream gauge network (see section 2.2) dictates the scale of prediction of upland water quality effects.

1.2 The Difficulty of the Problem

As an environmental modelling problem, the difficulty of the task defined above rates very highly. It is characterized by the following:

(a) natural complexity

Flows of water, sediment and nutrients, between and within media, each possess their own dimensions, time constants, spatial scales, throughputs and thresholds.

(b) spatial heterogeneity

The media (the atmosphere, land surface, subsurface, streams etc.) are heterogeneous 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 should not be hoping to 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. We seek to build a framework and models to characterise the physical system, providing a basis for assessing how to intervene and influence desired land and water quality outcomes more to society's benefit.

1.3 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) anticipate and stimulate the acquisition of high-leverage knowledge and data
(e) 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. It underpins the generic models selected for each subsystem type, their conceptual complexity and the spatial and temporal discretization intervals. The scale at which model outputs are required may also influence the prescription.

In order to sharpen some of the foregoing discussion, the relevant database that is available for modelling runoff, flow, erosion, sediment and nutrient concentrations in the Namoi Basin, NSW, Australia, is described in the next section. This is typical of databases that exist or can be constructed in Eastern Australia.

2. ASSESSMENT DATABASE: NAMOI BASIN

2.1 Brief Description of the Namoi Basin

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

The catchment lies within a region of highly 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 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. Permian-Carboniferous basement rocks of the Gunnedah Basin comprise basalt, acid volcanics and tuffaceous sediments, interbeeded with sandstones and conglomerates. Overlying these rocks are gently dipping successions of sediments which include shale and economic coal seams. Further west, the rocks of the Oxley-Surat Basin comprise shales and Pilliga Sandstone. In the far west of the catchment, deep Tertiary and Quaternary alluvium overlies a sequence of shales and siltstones. The youngest consolidated rocks of the catchment are the Cainozoic volcanics which outcrop extensively and define the Nandewar Ranges, Liverpool Ranges and the Warrumbungles. The weathering and erosion of these basic volcanics has produced the highly fertile alluvium of the Liverpool Plains in the vicinity of Gunnedah (Figure 1).

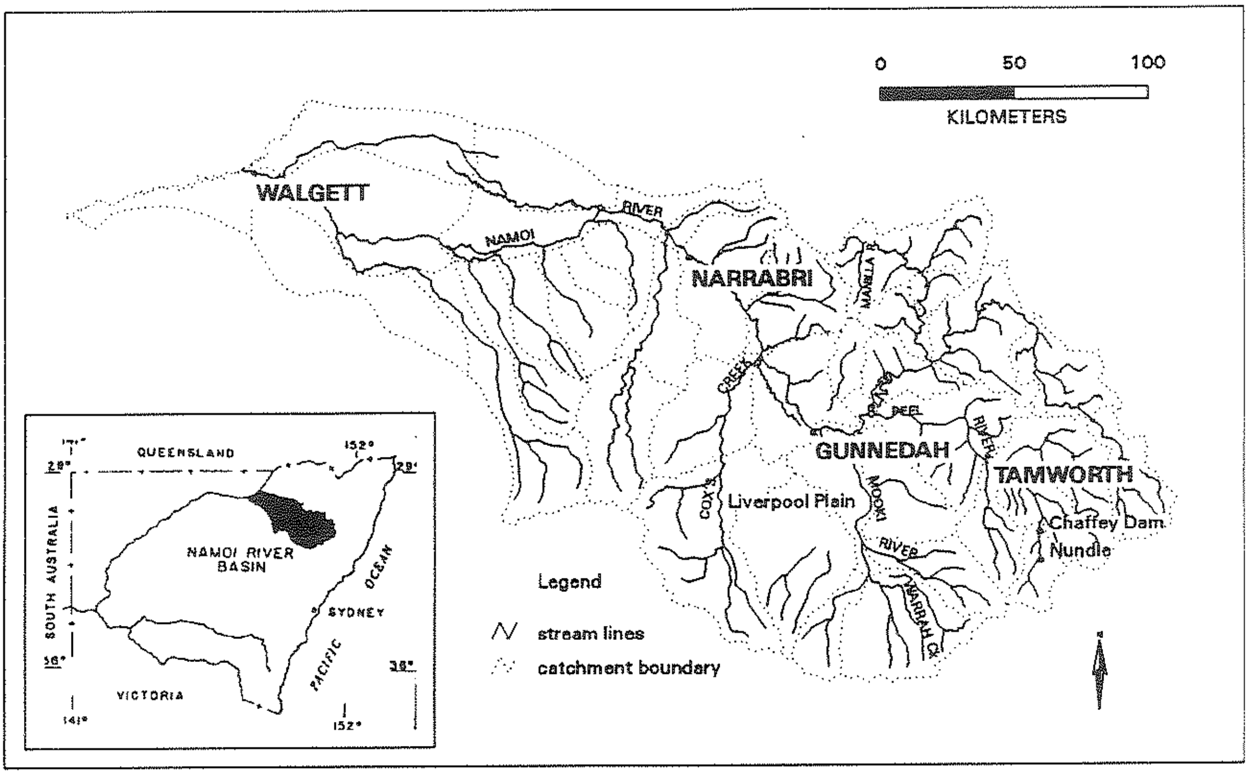

Figure 1: Location of the Namoi Basin

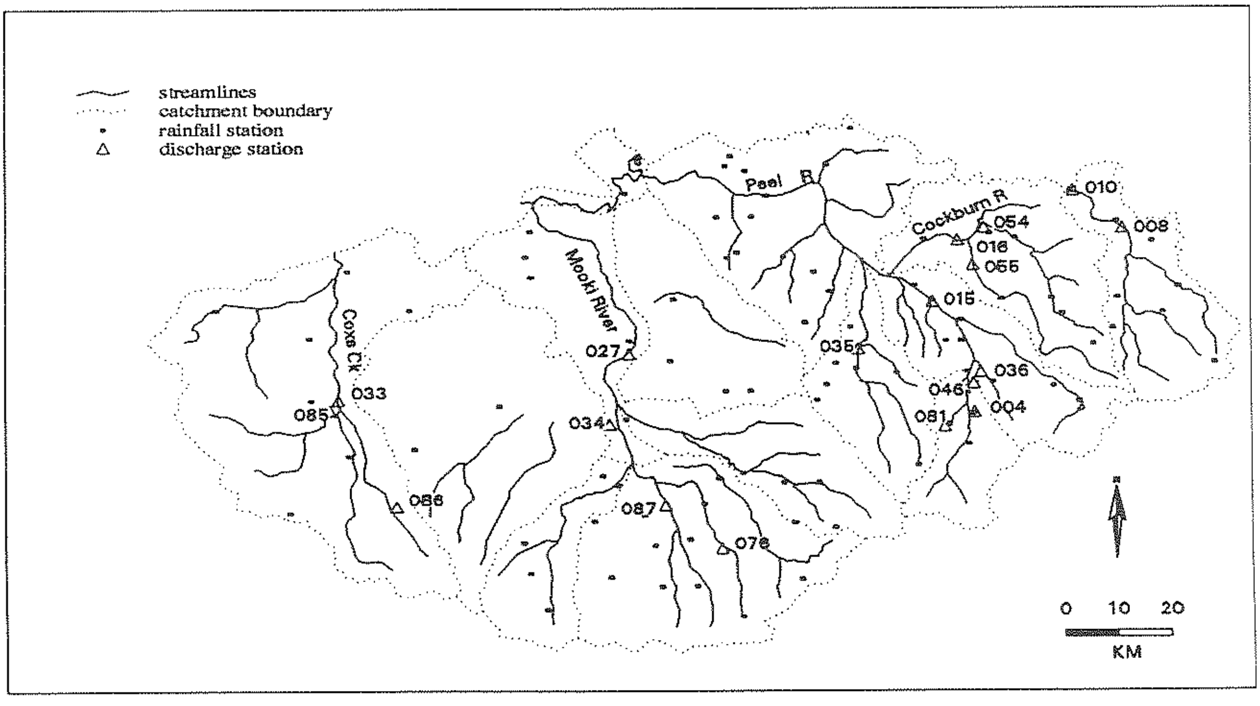

Figure 2: The precipitation-discharge measurement network for the southern uplands of the Namoi Basin.

The Namoi Basin is a highly productive agricultural area supporting beef and sheep grazing, wool production, and both dryland and irrigated cropping. Dominant winter crops include wheat and barley, with sorgham, sunflowers and cotton as the dominant summer crops. Intensive landuse includes dairying, cattle feedlots, piggeries and poultry farming. Approximately half of the catchment supports grazing, whilst ~23% of the catchment is used for grain, fibre or fodder cropping.

2.2 Climate and Discharge Network

Figure 2 shows the precipitation 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 2 catchments under 200 km^2 with measured discharge and their record length varies from 11 to 21 years. The density of concurrent raingauge stations in these smallest stream-gauged catchments ranges from 93 to 150 km^2 per gauge.

Hansen *et al.* (1996) have studied eight catchments in the Clarence Basin to the north-east to examine the predictive accuracy of a daily rainfall-runoff model. It was demonstrated that the stream-gauge rating and rain-gauge density were principal factors in the level of accuracy achieved. Duncan *et al.* (1993) found that rain-gauge 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.

The main point to be gleaned from this subsection is that precipitation and discharge databases, which are absolute necessities for inferring water availability and quality, are only available over scales of ~100 km^2 upwards and vary considerably in representativeness and accuracy, respectively. Any methodology for relating rainfall, runoff and water quality must take this into account.

2.3 Stream Water Quality Measurements

The area shown in Figure 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 5 key sites at which monthly grab samples are taken and 6 Central North West monitoring sites (CNWR) where weekly to fortnightly samples are taken. The authors have also instigated event sampling (~8 hourly) by landholders at Swampy Oak Creek, the Upper Mooki, Maules Creek, and the Namoi at Boggabri and Mollee, in order to assist the determination of relative sources of suspended sediment and nutrients throughout the basin. As with most basins, water quality measurements are spatially too coarse, and often temporally too recent, to permit the use or development of overly "sophisticated" models.

2.4 Spatial Data

Since the 1940s air photographs at approximately decadal frequency have been taken. These were initially at 1:18,000 scale but in the 1960s this changed to 1:80 000. In the 1990s the scale was 1:25 000 and photographs were available in colour for the first time.

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 Figure 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.

Digital elevation data are available at 1:200,000 scale for the basin and 1:25,000 for the Liverpool Plains catchments. Soils data are very highly aggregated in space while geological maps are available at a scale of 1:250,000.

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.

2.5 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. The ability to deconvolve the upland genesis of sediments throughout the basin seems proportional to the variety (and hence experimental cost) of tracers used for this purpose.

3. MODEL TYPES

In general, three distinct types of models have been developed to predict flows and concentrations of water quality variables (such as suspended sediments and phosphorus) either from upland precipitation in a catchment's tributaries or upstream flows and concentrations in a river reach. These can be classified as statistical/empirical, conceptual and physically based.

3.1 Statistical/Empirical Models

The feature of this class of models is their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables. For example, the rational method computes runoff as proportional to rainfall intensity versus catchment area with the constant of proportionality to be estimated. Similarly, an empirical relation of sediment loss versus catchment area has been developed for catchments in eastern Australia by Wasson (1994). The CMSS model (Davis and Farley, 1997) incorporates erosion factors for different land uses and soil types based largely on literature values.

None of the above models is designed to be event responsive but the finer detail of events often determines runoff volume and quality. The advantages of statistical/empirical models are their ease of use and the fact that they can be supported by coarse measurements.

3.2 Conceptual Models

These are typically more detailed in their conceptualization of catchment and/or stream processes. Conceptual catchment and in-stream models tend to represent flow paths as a configuration of stores connected by pathways, each store requiring some characterization of its dynamic behaviour. The well-known Stanford watershed model or HPSF is a highly parameterised representation of stores attempting to encapsulate the response of a catchment to precipitation. Typically, conceptual models are not spatially distributed, tending to lump representative processes over the scale at which outputs are to be simulated, but this need not be the case. The Universal Soil Loss Equation (Wischmeier and Smith, 1978) is the basis of several conceptual models some of which are spatially connected versions. The USLE relates sediment delivery to slope, length of slope, rainfall erosivity and soil erodibility. The latter two quantities are themselves predicted conceptually and empirically.

Conceptual models of in-stream transport processes include the aggregated dead zone model in Wallis *et al.* (1989) and the purely advective model of Dietrich *et al.* (1989).

3.3 Physically Based Models

These are derived from equations of continuity (mass and/or momentum) utilizing idealised assumptions of mathematical physics. Examples are the St Venant equations for flow, Richards equation for unsaturated flow, and the Boussinesq equation for saturated flow.

Physically-based models may be discretized finely in time, and in space, in an attempt to represent the spatial heterogeneity of the landscape (catchment or river morphology). Their main attraction has been the expectation that their spatially distributed model parameters could be measured in the field, but in general, this has now been rejected. Like all model types, because their representations are idealized to some extent, calibration of model parameters is essential to fit observed data.

The major disadvantages of physically based models are their idealization of the transport media, their computational demands and their requirement for intensive measurements of parameters or states. Often, such measurements are invented in the calibration phase, rendering the ultimate parameterization highly uncertain.

4. GUIDELINES FOR MODELLING FRAMEWORK

In constructing a modelling framework to address the problem defined in section 1.1, the following guidelines were utilized:

- 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).
- Utilize empirical information for determining those outputs or states which cannot be modelled conceptually or physically.

5. 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. The upland areas being modelled in the Namoi Basin include those in Figure 2.

5.1 Rainfall-Runoff Model

The conceptual rainfall-runoff model IHACRES (Jakeman *et al.*, 1990; Jakeman and Hornberger, 1993) is used to generate daily discharge, from rainfall and temperature inputs, at the catchment scale at which discharge records have been collected.

Like most conceptual rainfall-runoff models, it can predict discharge with catchment-scale observations of precipitation and discharge only. It does have several advantages, most of which are not shared with other conceptual types, viz.:

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

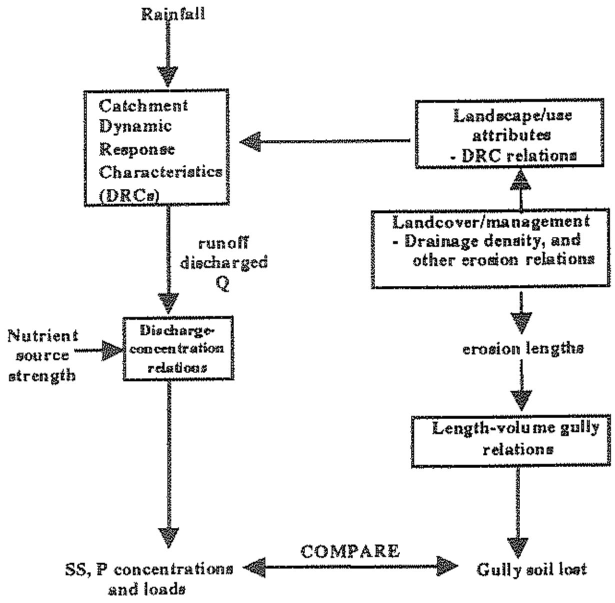

Figure 3: Modelling framework for upland catchments.

(ii) Its parameterization is highly efficient (5-7 parameters) and therefore can be estimated from relatively short periods of record (e.g. a few years of daily precipitation and discharge).

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

(iv) 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).

(v) DRC's can be related to landscape attributes e.g. quickflow recession rate accords well with drainage density (Post and Jakeman, 1996); potential catchment moisture storage is influenced strongly by vegetation cover (Post, 1996).

(vi) 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 (Post, 1996).

5.2 Discharge-Concentration Relationships

Relationships which allow material concentrations like suspended sediment and phosphorus to be derived from discharge are being sought. We know that this can be achieved for suspended sediment and hopefully it will be satisfactory for phosphorus by incorporating a source strength term for phosphorus levels in soil into the relationship.

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.*, 1977; Crapper and 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.

5.3 Spatio-Temporal Landscape Analysis

The aim of this analysis from air photographs is to assess the effect of climate, land cover and land management (as far as the latter can be determined) 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 landcover) and dynamic response characteristics (e.g. quickflow hydrograph peak or runoff ratio), estimated by the rainfall-runoff modelling exercises, can then be used to modify the IHACRES model parameters and in turn simulate the effects of climate on daily runoff historically and for any reasonably appropriate land cover/management scenarios. This involves the selection of subcatchment areas for comparison across space and time to control for one or more of geological type, slope, land cover type and management.

Comparison through time in the same subcatchment controls for geology, slope and sometimes land cover and management thereby allowing the effect of climate preceeding 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, to some extent, climate. So, for example, changes in erosion over the same 10 and 20 year periods have already been quantified for subcatchments with similar geology, soils and slopes.

The outputs of runoff and, using the results of the procedures outlined in section 4.2, 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.

6. IN-STREAM MODELLING COMPONENT

The upland modelling component has as its basic tool a generic rainfall-runoff model (IHACRES) linked to discharge-concentration models and an upland landscape-runoff response analysis. Similarly, 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 versus discharge in reaches (see Figure 4).

6.1 In-Stream Model

The model described in Dietrich and Jakeman (1997) has been developed to aid identification of the sources and sinks of sediment within reaches, and to route pollutant concentrations through the reaches of a stream network. The model has as its major features: 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 averaged flow rate is above a critical value and zero otherwise.

6.2 Discharge and Suspended Sediment - Phosphorus Concentration Relationships

Because of the poor understanding of how phosphorus in its various forms is transported and reacts along a reach of river, an empirical approach is being used to relate discharge and suspended sediment concentrations to phosphorus concentrations at a station. The relations will be calibrated at the sites available in the network.

6.3 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 active bank recession is expected on the outside of a bend, relatively straight but widening channel section, or upstream portion of the inside of a bend. Stream-reach and bank morphology changes over decadal times are being assessed using air photo analyses.

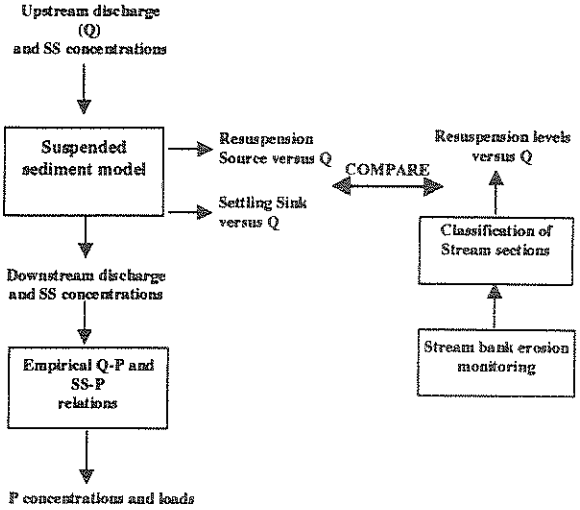

Figure 4: Modelling framework for the in-stream component.

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. 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 will be 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.

While full implementation of the prototype approach being developed would require substantial increases in the spatial resolution and temporal frequency of monitoring of both stream banks and sediment loads, the model should be useful for improving on dynamic estimates of sources and sinks of sediments and attached phosphorus.

7. STRENGTHS AND LIMITATIONS OF THE MODELLING FRAMEWORK

The framework presented here and currently being used in the Namoi Basin project 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 statistical or empirical to be limited in its ability to determine improved control options.

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. And 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 comes to hand.

Major improvements to the approach will come from better understanding of upland and in-stream nutrient source strengths and flowpaths.

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