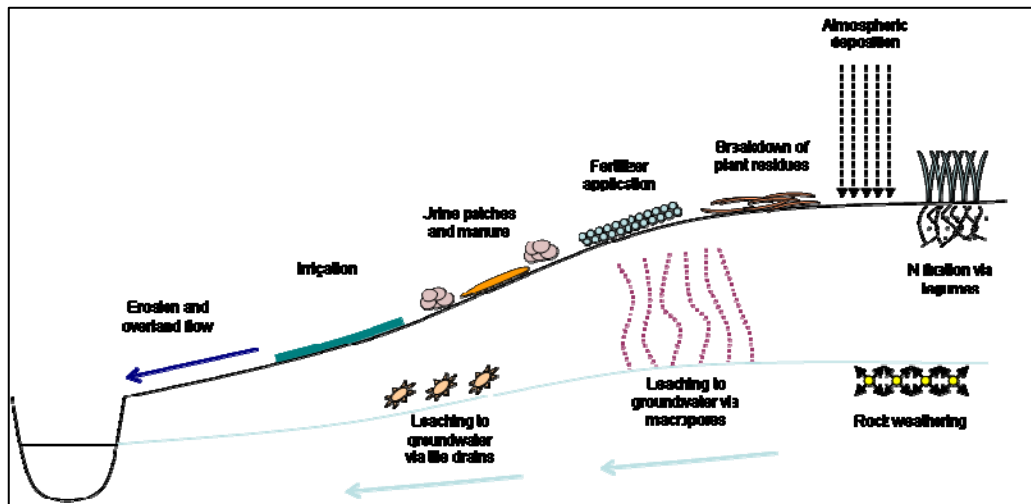




Modelling catchment-scale nutrient generation

Lachlan T.H. Newham and John J. Drewry

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Modelling catchment–scale nutrient generation

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EXECUTIVE SUMMARY

The aim of this report is to guide the ongoing development of nutrient generation approaches suitable for application in Australian catchments.

The report begins by presenting an overview of literature on Australian nutrient generation studies, and includes a summary of the primary considerations for constructing models to simulate nutrient generation. Among other suggestions, the importance of considering soluble nutrient sources via processes of leaching and groundwater contribution is emphasised.

A description of broad modelling approaches, potentially applicable for simulating nutrient generation is then made. The applicability of four categories of models, viz. generation rates-, process-, physics- and index-based approaches, is discussed. For application in Australian catchment-scale studies, less complex approaches such as generation rates and process-based model categories are suggested as most appropriate.

A comparison and evaluation of specific models viz. CMSS, CatchMODS, EMSS and E2, which are currently used in Australia, is then made. The specific features of these models are presented and critiqued. It is suggested that development be directed towards scenario-based assessment using models with node-link spatial structures, operating at daily time intervals.

Suggested directions for ongoing research, including improving representation of subsurface pathways and soluble nutrient components under a range of land uses, are suggested. Consideration of simulation of nutrient generation processes, the applicability of existing models and other general issues including potential enhancement to generation rates-based approaches are also presented.

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1 INTRODUCTION

This report is a contribution to the Land and Water Australia project CLW55 'Development of a Catchment Contaminant Cycle Model for Stakeholder Use' funded under the National River Contaminants Program (NRCP) of Land & Water Australia and by the Murray Darling Basin Commission. The Program commissioned CSIRO Land and Water, The Australian National University and the CRC for Catchment Hydrology to develop the next generation of catchment contaminant cycle models. Other researchers in the National River Contaminants Program were charged with delivering the new science to be incorporated into the model.

To foster the linkages necessary to bring this science together, the CLW55 project team held a scientific workshop on 23-24 March 2004 in Canberra (Cuddy et al. 2004). At the workshop six working groups were formed to advance particular aspects of the project.

Table 1 The six working groups in the CLW55 project.

Working Group	Chair	Email address	Notes
1 Salinity Effects	Ben Kefferd	ben.kefferd@rmit.edu.au	
2 Riparian Nutrients	Heather Hunter	heather.hunter@nrm.qld.gov.au	
3 Riparian Particulates	Lachlan Newham	lachlan.newham@anu.edu.au	
4 Nutrient Generation	Lachlan Newham	lachlan.newham@anu.edu.au	
5 In-stream Nutrients	Myriam Bormans	susan.cuddy@csiro.au	now Sue Cuddy
6 Co-ordinating Group	Kit Rutherford	kit.rutherford@csiro.au	

This report describes the findings of the Nutrient Generation Working Group which set itself to:

- investigate techniques for simulating catchment-scale nutrient generation; and
- identify shortcomings and directions for ongoing research.

Parts of this report are based on the following papers which were produced in conjunction with the CLW55 project:

- Drewry, J.J., Newham, L.T.H., Green, R.S.B., Jakeman, A.J. and Croke, B.F.W. (submitted) A review of nitrogen and phosphorus export to waterways in Australia: context for catchment modelling, *Marine and Freshwater Research*.
- Newham, L.T.H., Cuddy, S.M., Vertessy, R.A. and Jakeman, A.J. (2005a) Determining future directions in contaminant cycle modelling through an evaluation of existing modelling systems' In Proceedings of the 2005 International Conference on Simulation and Modelling, V. Kachitvichyanukul, U. Purintrapiban and P. Utayopas (eds), 17-19 January, Bangkok, Thailand, pp. 426-433.

2 BACKGROUND

Currently, there is substantial investment both in Australia and overseas in measures to improve stream ecosystem health in degraded rural and urban landscapes, and to maintain health in unimpaired systems. The principal focus is on reducing the generation and delivery to streams of contaminants such as nutrients, sediment, salt and pathogens; maintaining or restoring flow regimes; and managing physical habitat. There is urgent need for modelling approaches suitable for investigating the catchment-scale effects of common management interventions.

Appropriately constructed contaminant cycle models have a key role in supporting catchment management. They can inform policy to address water quality and environmental degradation concerns, and support the prioritisation of investment in catchment remediation. They can improve the focus of management intervention and evaluate best management practices. Importantly, they can increase confidence in natural resource management decision making by enabling simulation of the potential costs and benefits, a priori.

Several contaminant models have been successfully used to focus land management and inform policy debate. Examples include the Sediment River Network (SedNet) model (Prosser et al. 2001) which was applied as part of the Australian National Land and Water Resources Audit to determine critical sediment sources; the Catchment Management Support System (CMSS) (Davis and Farley 1997) which has been applied widely in Australian catchments as a planning tool for reducing nutrient loading; and the MUSIC model (Wong et al. 2001), used to predict how stormwater treatment can be used to manage sediment and nutrient loads in urban catchments.

With the success of contaminant models such as those described above, managers and policy makers are increasing their reliance on contaminant models not only as predictive tools but also as frameworks for communicating key aspects of catchment and stream management. This increased reliance on contaminant modelling results in the need for robust and credible tools. This is particularly the case for the simulation of nutrient generation where process understanding and hence subsequent modelling is often poor.

2.1 Report outline

The aim of this report is to guide the ongoing development of nutrient generation modelling. The report begins by describing key nutrient generation processes and presents a review of post-1996 studies of nutrient generation. Processes of nutrient generation and pathways are described. A description of existing catchment contaminant cycle models which incorporate nutrient generation components is then made. The review focuses on four models – the Catchment Management Support System (CMSS), the Catchment-scale Modelling of Diffuse Sources (CatchMODS) model, the Environmental Management Support System (EMSS), and E2. The strengths and weaknesses of these models for simulation of nutrient generation processes are identified and discussed. The models are also evaluated in terms of how they meet potential end-user requirements. Suggested directions for future model development activities are then described. This includes possible enhancements to the predictive capability of models and frameworks such as E2 for nutrient generation.

3 REVIEW OF CURRENT NITROGEN AND PHOSPHORUS GENERATION PROCESSES

This section presents an overview of Australian literature describing diffuse sources of nitrogen (N) and phosphorus (P). The review focuses on studies quantifying catchment-scale N and P losses. Much of the review material is sourced from Drewry et al (submitted) and is focused on post-1996 studies. Pre-1996 studies were comprehensively reviewed by Marston et al. (1995) and Young et al. (1996) and hence are not considered in detail here.

3.1 Introduction

Nitrogen (N) and phosphorus (P) are important nutrients required to maintain the productivity of agroecosystems. However, the mobilisation of both nutrients can have detrimental effects on waterways. Eutrophication in surface waters, and subsequent algal blooms result in the loss of, and changes in, the composition and abundance of species. Eutrophication can reduce the use of groundwater, drinking water and recreational activities (Davis and Koop 2001; Di and Cameron 2000; McDowell et al. 2004). In coastal lake and estuarine systems, the occurrence of algal blooms is of particular environmental and regional economic concern (Donnelly et al. 1996; Gabric and Bell 1993; Webster et al. 2001). However, there are surprisingly few published studies on N and P export to waterways in Australia, particularly in the valuable farming regions of south eastern Australia (Marston et al. 1995; Young et al. 1996). This has the potential to result in poorly directed remediation effort and lead to correspondingly little improvement in environmental quality.

The loss of nutrients from land originates from both diffuse and point sources. This report is focused on diffuse sources. In agriculturally dominated catchments, diffuse ie, non-point sources generally dominate inputs of N and P into streams (Davis and Koop 2001; Heathwaite 2003; McDowell et al. 2004). The bulk of P carried by streams in inland Australia is thought to be derived from P sourced from stream bank collapse and gully erosion of readily dispersible soils (Davis et al. 1998b; Wallbrink et al. 2003). In Murray Darling Basin river systems, it is likely that most of the P on river sediments is naturally derived from subsoils (Davis et al. 1998b). In contrast, nutrient exports from intensively farmed land in tropical Australian catchments have a high percentage in a soluble form, often attributable to fertiliser sources (Davis and Koop 2001; Hunter and Armour 2001).

In Australia, the effect of N on water quality has generally received less attention than P. In many freshwater and estuarine systems, N rather than P, can be the nutrient that limits weed or algal growth (Ford and Bormans 2000; Hart and Grace 2000). A low N:P ratio is associated with increased risk of dominance of cyanobacteria, affecting water quality (Ford and Bormans 2000). Much of the N research in Australia has focused on estuarine environments rather than freshwater (Hart and Grace 2000). Recent research suggests that N plays an important role, for example, in riparian zones (Rassam et al. 2003), irrigation (Mundy et al. 2003) and surface and groundwater (Davis and Koop 2001; Hunter 2000).

Many northern hemisphere nutrient studies were suggested by Young et al. (1996) to be inappropriate for Australian conditions. Several key reasons include:

- Australian N and P exports, particularly in disturbed catchments, are generally much lower than those found in northern hemisphere studies (Harris 2001). This is suggested as a result

of lower atmospheric deposition, lower fertiliser input and population densities (Harris 2001; Davis and Koop 2006);

- Australia exhibits a climate that is generally drier than the northern hemisphere, with long drought periods and a highly variable hydrological response, with the majority of nutrients transported in a relatively short period of time (Croke and Jakeman 2001; Davis and Koop 2006);
- Processes such as stream bank and gully erosion, macropore subsurface flow, and floodplain processes that are important in delivering nutrients to Australian waterways are generally not included in northern hemisphere models (Davis and Koop 2006); and
- Australia generally has poorer quality soils, more highly weathered landscapes and less intensive farming systems than many northern hemisphere farm systems (Harris 2001; Wasson et al. 1996).

3.1.1 Role of models

Due to the complex nature of catchment systems, the expense of monitoring programs and our desire to explore scenarios beyond otherwise observable conditions, modelling approaches are commonly used to assess catchment-scale nutrient generation. Models can play potentially important roles in evaluating changes in land use and management. Their use can assist evaluation of water quality trends and overcome difficulties presented by high temporal variability and limited water quality measurements (Molloy and Ellis 2002). However, improved representation of key nutrient generation processes is needed to improve the utility of modelling outputs and confidence in ensuing management recommendations.

3.2 Overview of diffuse nutrient sources and transport processes

Nitrogen and phosphorus are available from many diffuse sources and are subject to a variety of transport processes to waterways. This section presents a brief overview of these sources and pathways. Figure 1 presents a summary diagram representing diffuse N and P sources and transport pathways.

3.2.1 Nitrogen sources

Soil nitrogen inputs are available from sources such as nitrogen fixation via legume pastures, breakdown of plant residues, and fertiliser additions (Cameron et al. 2002; Pakrou and Dillon 2000). However, leaching of N frequently occurs via high N concentrations from grazing animal urine patches, rather than from direct fertiliser losses (Cameron et al. 2002; Di and Cameron 2000; Monaghan et al. 2002; Silva et al. 1999). Soil nitrogen is frequently present in soil organic matter and is not available for plant uptake or leaching unless mineralised to nitrate or ammonium. In years when drainage volumes are low, N fertiliser can be utilised without impact on waterways. In low drainage years, nitrate may accumulate in soil, and be displaced in subsequently higher drainage years (Eckard et al. 2004; Ridley et al. 2001). The cumulative nitrate load in a waterway will depend on the cumulative intensity of grazing and fertiliser use in a catchment (Eckard et al. 2004).

Recent research internationally and in south eastern Australia has identified N losses to groundwater, particularly from preferential flows through large soil drainage pores or macropores (Rasiah et al. 2003; Rassam et al. 2003), through mole and tile drainage systems under dairying (Eckard et al. 2004; Monaghan et al. 2005), under irrigation (Mundy et al. 2003; Pakrou and Dillon 1995; Pakrou and Dillon 2000), and from sheep-grazed pasture (Ridley et al. 2001).

3.2.2 Phosphorus sources

Sources of P to waterways include fertiliser, effluent, and natural sources of soil P. These sources have been reviewed and studied widely (e.g. Cameron et al. 2002; McDowell et al. 2004). Transport factors are also very important (Haygarth and Jarvis 1999), and are briefly discussed in a following section. However, it is the combination of source and transport factors which will determine overall P loss to waterways (Heathwaite 2003; McDowell et al. 2004).

3.2.3 Channel erosion and sediment-associated P loss

Many areas of Australia have soils that are subject to structural breakdown, contributing to gully and streambank erosion. Physical and chemical factors affecting such soil erosion were recently reviewed by Greene and Hairsine (2004). In the Southern Tablelands of south eastern Australia, soil erosion increases greatly as land is developed, particularly where active gully erosion is present (Neil and Fogarty 1991). Erosion has the effect of contributing quantities of nutrients, particularly P, which are adsorbed to soil particles. Gully erosion and streambank collapse continue to be a dominant source of P in many areas (Caitcheon et al. 1999; Martin and McCulloch 1999).

At the individual land use scale, Wallbrink et al. (2003) showed that surface soils contributed about 60% to offsite sediment-P loads in the Bundella Creek catchment, NSW. However, at the catchment outlet, 70% of sediment and 62% of sediment-bound P was from gully and channel erosion. Similarly, Newham et al. (2004) noted that 'channel sources (gullies and streambanks) dominate diffuse pollution' in the 985 km² Ben Chifley Dam catchment, an upland catchment of the Murray Darling Basin. However, evidence is less clear elsewhere (Martin and McCulloch 1999)

3.2.4 Overland and subsurface flow transport of N and P

Pathways for N and P movement have been discussed in a number of reviews and studies including Haygarth and Jarvis (1999), McDowell et al. (2004), Nash et al. (2002), and Cameron et al. (2002). Hydrology affecting nutrient movement can be divided into surface (overland flow) and subsurface pathways. Overland flow is an important pathway for dissolution of nutrients from surface soil, and large amounts of P can be transported via eroded soil particles (Davis et al. 1998b). There is considerable risk of P loss after intense rainfall or flood irrigation events particularly within short times of fertiliser application (Austin et al. 1996). The connectivity of the land to the waterway is also very important for P loss (McDowell et al. 2004; Sharpley et al. 2003), particularly in flood irrigation or subsequent management of excess irrigation water for on-farm reuse (Anon 1998).

Historically, it has been assumed that P is not readily transported through soil, but recent work refutes this assumption under some intensive land uses (Cox et al. 2000; Monaghan et al. 2002; Stevens et al. 1999). P is transported through soil via large soil macropores (Haygarth and Sharpley 2000). Similarly, leaching of more mobile P forms from farm effluent has been reported by Toor et al. (2004). Small intensively farmed areas (including fertilised pasture), land application of dairy effluent (Houlbrooke et al. 2004) and market gardens have high delivery ratios and can result in elevated N

and P losses. At a catchment scale, the subsurface pathway is emphasised by nutrient loss during stream baseflow when storm events are absent (Cosser 1989; McDowell et al. 2004).

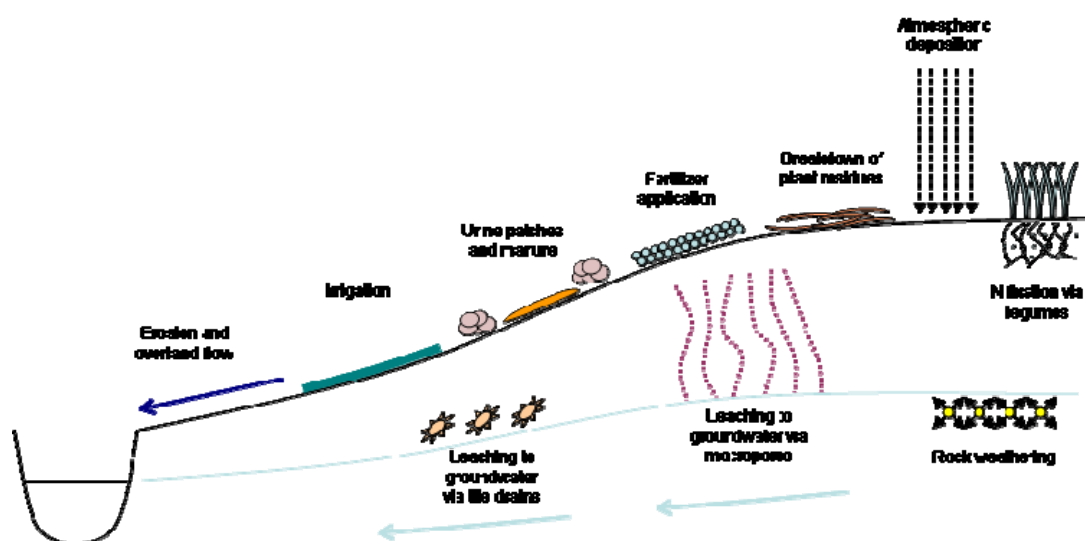


Figure 1 Diagram of N and P sources and transport pathways.

3.3 Studies of nutrient generation in Australian catchments

A comprehensive summary of Australian nutrient generation studies undertaken prior to 1996 is presented in the Nutrient Data Book of Marston et al. (1995). The Nutrient Data Book includes Australian review studies (published up to 1993) and international studies (published up to 1991). It was compiled to assist users of CMSS (see Section 4.3.1) to estimate long-term annual average nutrient generation rates under specified land uses and management practices (Davis and Farley 1997). The greatest number of studies was obtained from urban land (five studies for TN, and six studies for TP), followed by improved pasture.

Young et al. (1996) indicated that land use can be used as a simple predictor of nutrient loads, but that conclusion is based on limited literature. While limited adjustments can be made for differences between catchments, for example sediment-P relationships or runoff coefficients, it was found more difficult to account for other factors such as drainage and gully density, soil fertility and management.

Several studies in the Australian literature show intensive land uses such as dairying to have a relatively high generation of P and that single storm events may be responsible for high loads. Under dairying, for example, 69% of annual loss of total P (TP) was reported as lost in a single storm event (Nash and Murdoch 1997). Fleming and Cox (2001) showed 98% of TP was lost during a three-year period in overland flow, rather than as interflow through the A/B soil horizon. However, the amount of nutrient lost varied depending on rainfall, with most losses occurring during the wettest year. In contrast, Cox and Ashley (2000) showed that the magnitude of N and P loss was considerably less in low rainfall years. During low rainfall years, flow was primarily from groundwater discharge.

Consequently, rainfall and hydrology are important factors to consider for inclusion in catchment-scale models in Australia.

In the Hawkesbury-Nepean catchment, several studies have measured N and P losses from market gardening, dairying and semi-improved pasture. High nutrient exports, up to 200 kg N/ha/year and 15 kg P/ha/year for market gardens have been reported (Baginska et al. 1998). However, export rates for the whole of the subcatchment were estimated by a modelling approach to be 19.3 and 3.3 kg/ha/year for N and P, respectively. Losses on dairy farms, reported by Baginska et al. (1998) ranged from 2 to 6 kg P/ha/year and 4 to 6 kg N/ha/year depending on intensity of farming. Similar studies were also reported by Hollinger et al. (2001) and Hollinger and Cornish (2002). Market gardens and dairy pasture represent a high source risk. It was also found that semi-improved pasture had much greater exports than bush land (Hollinger and Cornish 2002).

Drainage through soil is an important pathway for N losses under dairying. In a Victorian dairy field leaching study, nitrate leaching exports from equivalent N applications (Eckard et al. 2004) were generally less than other global studies (e.g. Monaghan et al. 2005). However, the nitrate concentrations for these types of studies would be likely to have exceeded waterway guidelines for weed and algal growth. Note that such studies do not take account of factors important at catchment scales (e.g., dilution and in-stream processes).

Clearly, nutrient export data in published studies is varied, depending on source factors including land use, farm and management practices, climate, and soil. Davis et al. (1998b) noted that a considerable amount of P is trapped in farm dams prior to reaching the waterway. Other catchment factors affecting the source, transport, subsequent deposition and delivery of nutrients, including farm and riparian zone characteristics and management, are clearly important. Indeed, Chudleigh et al. (2000) recommended future research should focus on the scope for interventions along waterways, land use and practices, and nutrient export, with incorporation of these factors into catchment models. In an associated report, Newham et al. (2005b), discusses a model of particulate trapping in riparian buffer zones which was developed for use at catchment scales. This model provides the capability to simulate the effects of riparian buffer establishment and addresses some of the recommendations of Chudleigh et al. (2000).

3.3.1 Soluble versus sediment-bound nutrients

Although many studies have examined TN and TP exports, and sediment-bound N and P, relatively few have considered the soluble components, particularly for P. This section summarises published Australian studies that include soluble forms of importance to waterway health, and discusses research which should be considered for the development of catchment models.

The form of phosphorus is likely to depend on both source and management factors. Caitcheon et al. (1999) and Davis and Koop (2001) described that the bulk of P carried by inland streams is derived from erosion of subsurface soils. In contrast, other intensively farmed regions show a high percentage is attributable to fertiliser (Davis and Koop 2001; Hunter and Armour 2001). For example, Nash and Murdoch (1997) showed that 93% of the P lost annually for a dairy site was in dissolved form. Most runoff occurred when soil was saturated, and so the authors suggested that riparian buffers would therefore be unlikely to reduce P losses, given the high percentage of dissolved P.

A number of studies in South Australia and Victoria show dissolved forms of nutrients including P to be important. Catchment groundwater discharge, even in low rainfall conditions, is an important

pathway for N and P loss (Cox and Ashley 2000). Similarly, environmentally significant concentrations of nitrate and P are moved in both drainage and overland flow (Stevens et al. 1999). Cox and Ashley (2000) showed that catchment discharge contained 100% dissolved P so they concluded that estimation of TP loss based on sediment (particles $>45\mu\text{m}$) would be inappropriate during periods of low rainfall and flow. Macropore flow (i.e. through large soil pores) was also found to be an important pathway for P loss in the study of Kirkby et al. (1997). It was shown that P transport to subsurface horizons was more dependent on hydrology and presence of macropores, than on soil chemistry. These studies, and that of Cox and Pitman (2001), highlight the importance of dissolved nutrients when flow is predominantly from groundwater discharge.

Overland flow is also an important pathway for TP and dissolved reactive P (DRP) loss under dairying, with single storm events often responsible for high loads. For example, 69% of annual TP loss was reported as lost in a single storm event in Victoria by Nash and Murdoch (1997), while Fleming and Cox (2001) showed 98% of TP loss was in overland flow during a three year period. However, observed losses vary considerably depending on rainfall, with most losses occurring during the wettest year, while losses in dry years were much less (Fleming and Cox 2001). Exports of TP from a range of sites in Victoria and NSW (0.01–0.56 kg P/ha/year) are summarised elsewhere for a range of land uses and conditions (McCaskill et al. 2003).

The relative proportions of soluble and particulate N and P also vary between land uses and land practices. Soluble P was the dominant form from both intensive irrigated and dryland dairy pasture (Hollinger and Cornish 2002), while particulate P was dominant from market gardening (Hollinger et al. 2001). Runoff from market gardens contains a greater proportion of soluble N than other land uses, potentially reflecting higher inputs of fertiliser N. Soluble P also dominated dairy runoff (Cornish et al. 2002). Of note is that this study was on a dryland dairy farm with no regular applications of fertiliser P, although P exports were lower than more intensively farmed dairy units in the region.

Similarly, evidence of the importance of dissolved P to nutrient exports in less intensive sheep-grazed dryland pastoral systems has been reported by Johnston et al. (2003) in the Wagga Wagga region of NSW. The soluble proportion of P loss was higher in improved pasture runoff plots which received more frequent fertiliser applications and heavier grazing, than in the native pasture (Johnston et al. 2003). These studies suggest that soluble P export is important from dryland farms. Representation of these processes needs to be considered in development of future catchment models.

There have been few attempts to synthesise data on the dependence of forms of P and N on land use in Australia (Harris 2001). In pristine, forested catchments N and P exports are low and the predominant form of N is dissolved organic N, whereas after clearing exports increase and the predominant form of N is dissolved inorganic N (Harris 2001). From studies in the Hawkesbury–Nepean River catchments, Harris (2001) noted that, in the absence of wastewater discharges, dissolved reactive P was roughly a constant proportion of TP (10–30%). Widely varying contributions of subcatchments to dissolved and particulate P, depending on land use and urban development, were reported by Viney et al. (2000).

The ratio of soluble to particulate P varies with land management and use. Hence, the effectiveness of riparian buffers to remove dissolved N and P may not be adequate (Hunter 2000; Kirkby et al. 1997; McDowell et al. 2004; Nash and Murdoch 1997). Riparian vegetation and wetlands provide an opportunity for removal of nutrients, although may have a finite lifespan and once saturated they may act as a source (McDowell et al. 2004).

McKergow et al. (2003) found that in a small agricultural catchment improved riparian management reduced sediment exports, (a likely result of reduced stream bank erosion), but there was little effect on overall N exports, TP concentration and loads, although the soluble P proportion had increased. Although a recent Queensland study showed grass riparian strips were more effective at filtering sediment than forest buffers (McKergow et al. 2004), there has been little detailed research into the effectiveness of N removal by buffer strips in Australian systems (Hart and Grace 2000).

It is therefore of concern that dissolved nutrients may not be adequately included in catchment models, particularly when evaluating riparian management, as some models assume only sediment-bound nutrients. Where possible, integration of published data into catchment nutrient models would therefore be worthwhile. A major gap in knowledge is the capacity to predict different N forms entering waterways in Australia, as commonly used models predict TN (Hart and Grace 2000). Our review has indicated that many agricultural systems export dissolved P and N from both overland flow and soil drainage pathways. These pathways need to be taken into account in catchment-scale modelling. The great variety of landscapes in Australia preclude the use of a single model in all instances.

3.3.2 Effect of scale: small plot to catchment-scale

The ability of models to predict total or dissolved nutrients is often related to the scale of model development and application, and conditions under which measurements were made. Issues associated with scale are therefore briefly discussed in this section.

Much of the available nutrient export data has been derived from small-scale field or plot trials. However, these do not always retain the pathway linkages to water, particularly at catchment-scales (Heathwaite 2003). Very few studies for example, have attempted to link transport factors from lysimeter-based experiments to streams, although lysimeter-based processes have been incorporated into larger-scale nitrogen models (Di and Cameron 2000). At the plot scale, soil and crop type, nutrient cycling and leaching dominate (Quinn 2004), while hydrological processes dominate at the hillslope scale, with nutrient mobilisation related to source areas with high transport capacity (McDowell et al. 2004; Nash et al. 2002; Quinn 2002). At a large catchment-scale, key influences include variability of land use, rainfall and topography (Quinn 2004).

Scaling-up techniques have been noted internationally as an important area of further research (Quinn 2002), although scaling-up is associated with considerable uncertainty (Heathwaite 2003). Connectivity issues have been noted as important but requiring research, which could be potentially achieved by models such as modified P and N index models (Heathwaite et al. 2000), see Section 4.2.4. Linking watershed nutrient export with water quality remains under-researched, particularly at edge-of-field (Heathwaite 2003), but studies in this area are increasing. Similarly, one of the major limitations to understanding N processes at larger scales is the inability to scale up from smaller scale processes because there has been little research at larger scales conducted in Australia (Hunter 2000). Clearly, scale issues are important to consider in the ongoing development of nutrient generation approaches.

One of the few studies that has attempted to link small plot and farm scales in Australia was reported by Cornish et al. (2002). The study showed that concentrations of soluble P from dairy farm pasture runoff was dependent on scale (1 m² to 140 ha) but the effect of scale was surprisingly small. In contrast, Barlow et al. (2005) showed that under flood irrigation in Victoria, paddock-scale P exports could not be used directly to estimate farm-scale exports as P concentrations and loads decreased

between paddock and farm scales. The transport between source paddocks, drainage channels (Barlow et al. 2003) and streams, and therefore riparian assimilation requires further research for use within catchment models.

Plot-scale nutrient generation studies do not take account of many factors important at catchment scales. Such factors include stream dilution effects of intensive farming drainage with, for example, less intensive land use or native forest drainage. In-stream processes including attachment of P to sediment particles, riparian removal of N and P from drainage water or overland flow, and trapping in farm dams are also important factors at the catchment-scale.

4 DESCRIPTION OF EXISTING MODELLING APPROACHES

This section describes several existing modelling systems and presents an assessment of their utility for modelling nutrient generation. These models were selected for evaluation for the following reasons. Firstly, all models are applicable for widespread use to inform management decision making. Secondly, the models represent the current state of the art in modelling nutrient generation processes in Australia. Finally, the models are sufficiently different in their scale and method of operation to enable useful comparison of their features to guide ongoing model development activities.

4.1 Contaminant cycle model requirements

To support effective catchment management there is a need for robust, credible and thoroughly tested modelling systems and underlying model components. To meet these needs the following general requirements for catchment contaminant modelling have been collated (Newham et al. 2005a):

- adequate simulation of hydrologic and biogeochemical processes under current management conditions (Newham et al. 2004a);
- identification of critical source areas that currently, or potentially, contribute high loads of nutrients and other contaminants to streams (Newham et al. 2004a; Heathwaite 2000);
- the potential to simulate the impact of current and future land management practices on spatio-temporal outputs reaching surface waters (Newham et al. 2004a);
- the potential to simulate the impact of current and future in-stream management practices (Croke and Jakeman 2001);
- sensitivity to climate variability (Newham et al. 2004a);
- modest and readily available input data requirements;
- clearly stated assumptions (Croke and Jakeman 2001);
- able to be comprehensively tested;
- possess strong visualisation capabilities to enable results to be effectively communicated to users; and
- short model processing times.

The above list is non-exhaustive and may change depending on the nature of the specific issue being addressed. However, the list provides a useful starting point for considering the applicability of nutrient generation approaches. These requirements should be considered in the following description and comparison of modelling approaches.

4.2 Modelling approaches

This section briefly overviews the types of catchment-scale models in use for modelling nutrient generation in Australian catchments. We categorise nutrient generation models into four main approaches:

1. generation rates-based;
2. process-based;
3. physics-based; and
4. index-based.

Some models may contain a mix of modules from these categories, so the distinction is not always sharp (Drewry et al. submitted).

4.2.1 Generation rates-based

Generation rates-based approaches, often called empirical models, or sometimes export coefficient or metric models, are based on deriving responses from observations of data and are generally the simplest category of nutrient models. Parameter values may be obtained by calibration using observed water quality data, but more often are transferred from experimental sites where some calibration of models is possible (often for a single land use). Generation rates-based approaches are useful to identify sources of nutrient generation, but are very often catchment specific (Letcher et al. 1999; Merritt et al. 2003). If relationships with potential drivers can be derived however, broader application of generation rates-based models could be made.

Generation rates models take no account of spatial patterns within the catchment elements to which they are applied. However, more complex and dynamic models may be no more superior than generation rates-based models in their predictive capabilities (Letcher et al. 1999; Merritt et al. 2003). Letcher et al. (1999) indicated that many generation rates-based models are based on statistical analysis of catchment data and are therefore ideal for within-catchment analysis. However, Donnelly et al. (1998) noted that, although generation rates-based models can give accurate predictions under conditions representative of original data sets, little insight is obtained into the causes of the observed relationships. CMSS, EMSS, and in practice, E2, are examples of generation rates-based models in use in Australia. These models are discussed later in this report.

4.2.2 Process-based

Process-based models are typically represented by a series of internal storages, and usually include transfer mechanisms (Donnelly et al. 1998; Merritt et al. 2003). In contrast to generation rates-based models, process-based models are based on knowledge about nutrient generation processes. These models can provide an indication of qualitative and quantitative effects of land use change without the need for large amounts of spatially and temporally distributed input data. Alternatively, lumped process-based models can disaggregate a catchment into linked sub catchments. Process-based models are typically calibrated against observed data including stream discharge and nutrient concentration data and therefore rely on suitable observed response data, but may have a number of 'best' parameter sets (Merritt et al. 2003; Viney et al. 2000). Process-based models are in many cases a sensible compromise between physics-based and generation rates-based models. Process-based models are particularly suited to long-term prediction in large catchments (Viney et al. 2000).

CatchMODS is an example of a predominantly process-based model and it is described later in this report.

4.2.3 Physics-based

Equations for physics-based models are often derived at small plot scale under specific conditions (e.g. soil solute transport), but in practice are often used at much larger scales. This has drawn criticism as to their broader applicability (Donnelly et al. 1998; Merritt et al. 2003). Example models with nutrient generation capabilities include the Chemical Runoff and Erosion from Agricultural Management Systems model (CREAMS) (Foster et al. 1980), with modified version, GLEAMS (Leonard et al. 1987). The physics-based soil erosion and transport model, Watershed Erosion Prediction Project (WEPP) (Flanagan et al. 1995) is another example. WEPP, developed in the United States, requires detailed knowledge and inputs including estimates of characteristics such as crop growth, cover, residue, management practices, soil roughness, hydraulic conductivity (Merritt et al. 2003). Model complexity, computational requirements and associated error accumulation of these, and similar physics-based models limit their applicability for estimating catchment-scale nutrient exports (Merritt et al. 2003). This is particularly the case in data-sparse catchments, common in Australia (Letcher et al. 1999).

4.2.4 Index-based

To address nutrient-related water quality issues, a range of index-based modelling approaches are in use. Such techniques have been applied widely for nutrient management particularly in the United States and in Europe (Sharpley et al. 2003). The principles of index-based approaches are to rank site vulnerability of nutrient loss by accounting for source and transport factors with modifications for local conditions (Sharpley et al. 2003). Source factors may include soil nutrient levels, fertiliser, and where appropriate, effluent management. Transport factors include erosion, leaching, runoff and the 'connectivity' or land connection to the waterway. Index-based approaches are used to identify areas of greatest nutrient export or so called critical source areas (Heathwaite 2000).

Index-based approaches were originally developed to assess P loss risk at the field scale (Sharpley et al. 2003) and were not designed to predict actual P loss from fields or catchments. Suggestions by Sharpley et al. (2003) included incorporation into integrative tools with mapping databases. The index approach has been used at larger than field scale for P and N index assessments within small catchments (Heathwaite et al. 2000; McDowell et al. 2002). Some of these concepts have been applied at catchment scales in Australia. Newham et al. (2002) used the index approach of Heathwaite et al. (2000) in the Ben Chifley Dam Catchment of NSW to help identify potential sources and transport pathways of diffuse nutrients and prioritise management. Newham et al. (2002) increased the scale by approximately three orders of magnitude, and made modifications to improve the representation of connectivity by considering gully erosion pathways. Figure 2 shows an example P index from the Ben Chifley Dam catchment. Modifications implemented as part of the Ben Chifley Dam catchment application included:

- the use of multiplicative, rather than additive, relationships between source and transport factors, so that if, for example, surface runoff was low but soil P was high, then the risk of P loss would be low;
- inclusion of a distance-to-stream measure as part of the transport factor; and
- continuous scaling of selected source factors.

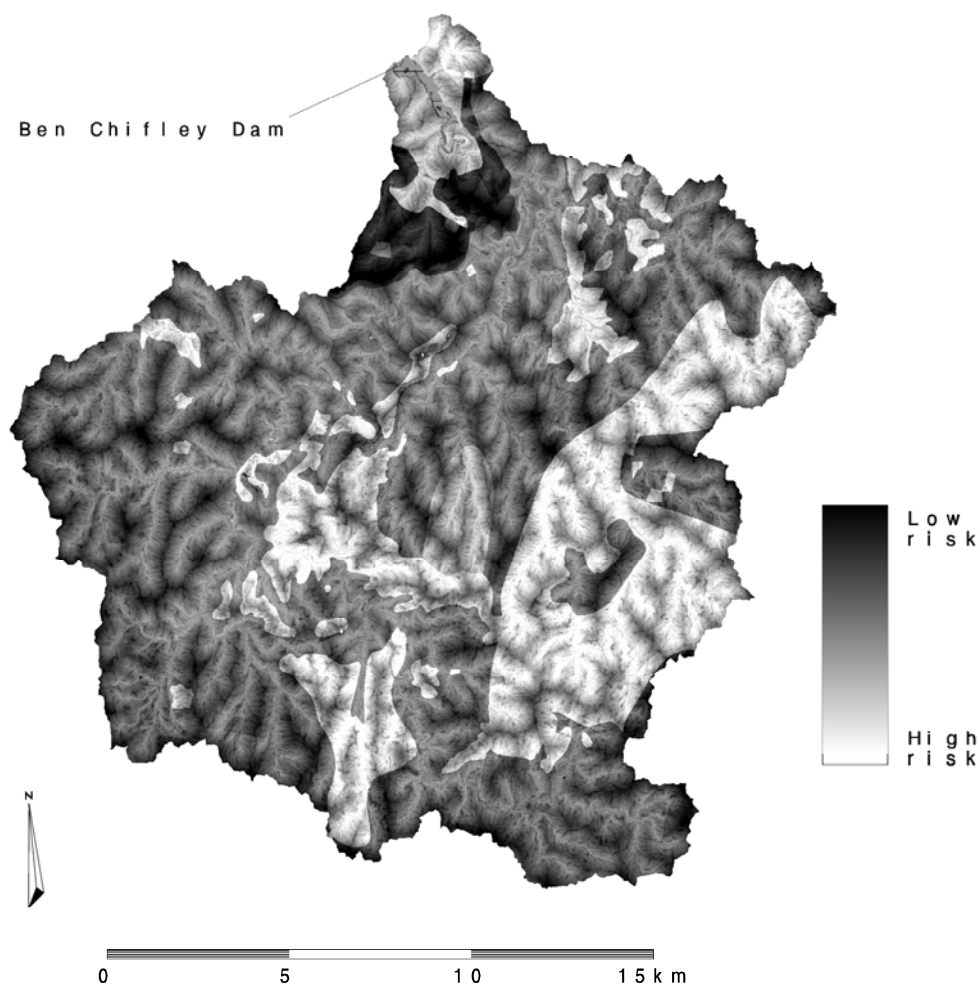


Figure 2 P index developed for the Ben Chifley Dam catchment, NSW (source Newham et al. 2002).

4.2.5 Discussion of modelling approaches

The choice of the model type is often governed by the emphasis of the model developer and the tools they have available (Merritt et al. 2003). However, a common misconception is that model accuracy increases with complexity (Letcher et al. 1999; Merritt et al. 2003). Complex models, particularly physics-based models, may suffer from error accumulation and lack of readily available input data. In contrast, simple models may perform equally as well or better than complex models in terms of their predictive capability (Jakeman and Hornberger 1993) but may not give insight or improve user understanding of key processes. Generation rates-based models and simple process-based models are thought to be more appropriate than physics-based models for estimating nutrient exports in catchments (Letcher et al. 1999). Similarly, process-based approaches, and some generation rates-based models, are useful because they allow investigation of catchment source strengths and have good general interpretability of results (Merritt et al. 2003). Predictions from water quality models are subject to considerable absolute error, and should therefore be used with caution when determining absolute amounts, although their ability to rank alternative management strategies is much more reliable (Moore and Gallant 1991). Index-based approaches are less likely to be constrained by a lack of input data and provide very good representation of catchment source strengths; however they do not represent nutrient generation processes explicitly and do not provide direct quantification of nutrient movement. As a result it is difficult to comment on their level of error

although it is expected that it would be of a similar magnitude to generation-rates and process-based models.

To meet requirements of end-users e.g. catchment managers and government agencies, Heathwaite (2003) has suggested that effort needs to shift towards developing models that are simple to use and easy to apply.

Lumped models treat a catchment as a single unit with averages over the catchment area, while distributed models make predictions that are distributed in space with variables representing local averages (Bevan 2000). Croke and Jakeman (2001) also noted that further progress is needed on the difficult problem of assessing land use effects within catchment models. In addition, current catchment models do not typically incorporate effects of land use changes over time.

4.3 Example models

This section presents an overview of selected models used by catchment managers to estimate nutrient exports in Australian catchments. In line with recommendations made in Section 4.2.5, relatively simple, widely available models were selected for assessment purposes in preference to more complex models. The following four models are reviewed:

- Catchment Management Support System;
- Catchment-scale Management of Diffuse Sources model;
- Environmental Management Support System; and
- E2.

4.3.1 CMSS

The Catchment Management Support System (CMSS) is designed to assist catchment managers to assess the effects of land use and management policies on long term nutrient loads delivered to streams (Davis and Farley 1997; Marston et al. 1995). CMSS has been widely used in Australia as an initial planning tool because of its simplicity, ease of use and ease of results presentation (Davis et al. 1998a; Gourley et al. 1996).

CMSS includes four modules:

- a database module describing catchment land uses, spatial attributes, nutrient generation rates and management practices;
- a policy module which allows the user to set up and modify policy sets;
- a predictive module; and
- an interrogation module which allows the user to examine the basis of load and cost predictions, where data was obtained and how variable or relevant it is.

The predictive module calculates nutrient loads by summation of the area per land use multiplied by a nutrient generation rate per unit area. There is also an ability to include point source inputs (Davis and Farley 1997; Letcher et al. 2002). An expert system is provided to help narrow the range of nutrient generation rates, a range of values is generated reflecting our generally limited understanding of nutrient generation processes (Letcher et al. 1999). A single generation rate is assigned to a land use. Many different land uses can be described to capture spatial variability in

biophysical factors, e.g. 'grazing on low fertility soils' would be assigned a different generation rate to 'grazing on high fertility soils'.

CMSS has a subcatchment network structure where loads are accumulated (and attenuated) through the network to give predictions for each subcatchment.

CMSS does not model the hydrology of catchments (Letcher et al. 1999). This is one of the major limitations of this model, given the importance of flow when estimating nutrient exports (Cosser 1989; Letcher et al. 2002; Rosich and Cullen 1982) and understanding the release and transport of nutrients. However, more accurate representation can be gained by comparing loads derived from CMSS against load estimated from observed data (Davis and Farley 1997; Joo et al. 2000). When the CMSS model stream routing and assimilation functions are not used, CMSS predicts potential nutrient loads which are inevitably higher than observed (Joo et al. 2000; Letcher et al. 2002). Baginska et al. (2003) suggest that particular care is needed when applying the model in large catchments as nutrient loads are often over-estimated relative to observations.

A study by Baginska et al. (2003) noted that unit-area models such as CMSS are indicative of long term nutrient generation, and therefore may not compare well with measured annual loads for a particular year due to high variability of rainfall and runoff. This is particularly important when interpreting short-term nutrient generation studies. Letcher et al. (2002) pointed out that, in general, CMSS is not used to provide an accurate estimate of loads, but rather to provide preliminary information of relative source strengths of different land use and management options.

4.3.2 Catchment-Scale Modelling of Diffuse Sources (CatchMODS)

The CatchMODS modelling system is designed to simulate existing conditions and the effects of management activities on the quality of receiving waters at catchment scales. The modelling system integrates hydrologic, sediment and nutrient export models and includes an economic component to evaluate the effects of management scenarios on nutrient and sediment delivery to receiving waters (Newham et al. 2004b). CatchMODS encapsulates the drivers of climate and associated hydrologic factors, the topography of a catchment, land use and riparian management practices and point sources of pollution. Through considering these drivers the modelling system can be used to simulate the effects of management change.

The modelling framework includes processes used in the SedNet model (Prosser et al. 2001) including spatial representation based on linked river reaches and subcatchment units. CatchMODS uses GIS and lumped modelling at stream reaches and subcatchment units (Newham et al. 2004b). The sediment submodel in CatchMODS uses processes represented in the SedNet model, including gully, hillslope and stream bank erosion. Improved spatial scale modelling in CatchMODS has enabled improvements to the quality of spatial data inputs compared to SedNet. Specifying gully erosion severity and assigning corresponding erosion rates are enhancements implemented in CatchMODS.

The hydrologic sub model used is the conceptual IHACRES rainfall-runoff model (Jakeman et al. 1990). The IHACRES model, with its low level of complexity (six parameters), reliably reproduces measured hydrographs and is therefore useful for applications in data sparse catchments (Croke and Jakeman 2001). The quality of predictions using IHACRES, as with any such model, are however influenced by rain gauge density, stream gauge rating quality, and catchment response dynamics, particularly baseflow (Hansen et al. 1996).

The nutrient modelling component simulates TN by using three sources of N, namely sediment-associated, groundwater-associated and point source inputs. Nitrogen losses in stream reaches are estimated by an exponential decay using channel area, although this requires further testing (Newham et al. 2004b). TP export is estimated in CatchMODS directly from observed suspended sediment load, based on the assumption that P is transported on sediment particles, which was supported by the water quality data for Ben Chifley (Newham et al. 2004b). However, as previously discussed, this is likely to be different in intensively farmed catchments, or coastal areas. CatchMODS is also likely to underestimate N and P losses from intensive farmland given the current reliance on the erosion submodel.

CatchMODS is based on a series of linked river reaches and associated subcatchment areas. The modelling is lumped at these stream reaches and subcatchment units and thus management prescription extends to the same scale (Newham et al. 2004b). There are six modelled nutrient inputs to an individual river reach in CatchMODS:

- upstream tributary inputs (except for first order streams);
- point source inputs;
- groundwater associated inputs;
- hillslope erosion;
- gully erosion; and
- streambank erosion.

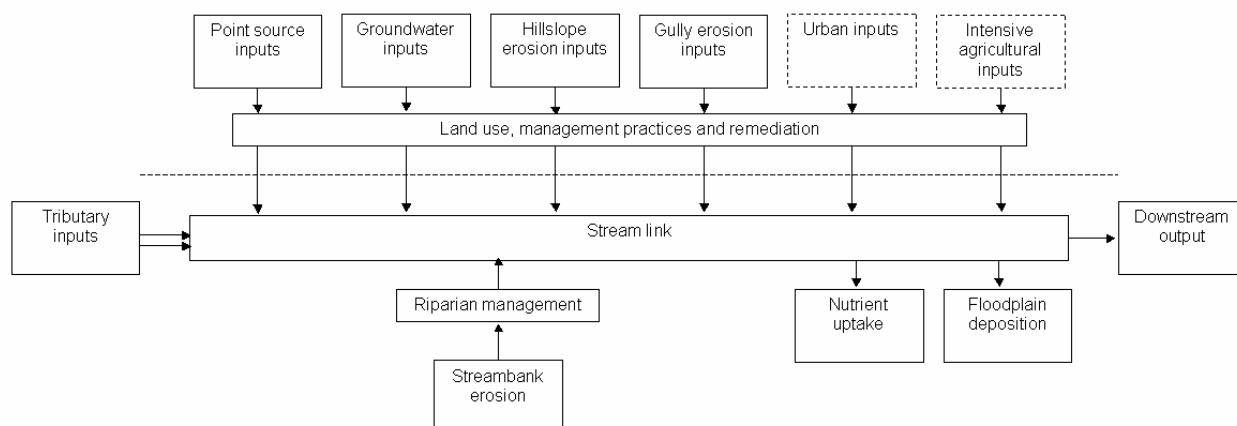


Figure 3 Components of an individual river reach-subcatchment modelling unit in CatchMODS.

The modelling framework is designed to allow identification of priority subcatchments for management intervention to include adequate simulation of hydrologic processes and climate variation, identification of critical source areas (parts of catchments contributing high loads to streams), and the potential to simulate management changes (Newham et al. 2004b). Although riparian revegetation and gully management are modelled, the effects of the establishment of riparian buffers are not (Newham et al. 2005a).

The ongoing development of the model aims to incorporate a pathogen modelling capability and an improved representation of pollutant generation from urban land uses. It is also planned to modify the model to represent pollutant generation and transport processes at a daily timestep in preference to the steady-state representation currently used.

4.3.3 Environmental Management Support System (EMSS)

The EMSS is a lumped process-based catchment-scale model used to estimate daily runoff and pollutant loads to receiving waters and to assess the impact of changes in land use and land management. The model is sensitive to changes in climate, reservoir operations, land use and land management practices (Vertessy et al. 2001) and scenarios for implementing these changes can be included. EMSS is composed of three linked submodels: a runoff and pollutant export model; a streamflow and pollutant routing model; and a reservoir model.

The runoff and pollutant export submodel operates on individual subcatchments to provide daily estimates of streamflow, suspended sediment, TP, TN and pathogens. In contrast to annual pollutant load reporting in CatchMODS, pollutant loads in EMSS are predicted daily (Vertessy et al. 2001). Daily rainfall and potential evapotranspiration data are needed to estimate daily runoff, which is partitioned into event and baseflow components. These flow components are multiplied by user-specified generation rates to estimate daily loads. Loads are predicted by a generation rates-based approach using estimates of event mean concentration (EMC) for stormflow and the baseflow runoff volume by dry weather pollutant concentration (DWC) (Cuddy et al. 2001; Merritt et al. 2003). Different EMC and DWC values can be allocated to subcatchments, depending on land use (Vertessy et al. 2001). However, EMC and DWC have been noted to be highly variable. Further research, supported by event-based water quality data collection, is required to further refine this approach.

The rainfall-runoff component of the model originates from the SIMHYD model (Chiew et al. 2002). The reservoir model simulates regulation of river flows, and traps pollutants and accounts for the evaporative losses from large reservoirs.

Like the spatial structure of CatchMODS, EMSS subcatchments are linked using a node link system. A diagram of the linked submodels of EMSS is shown in Figure 4.

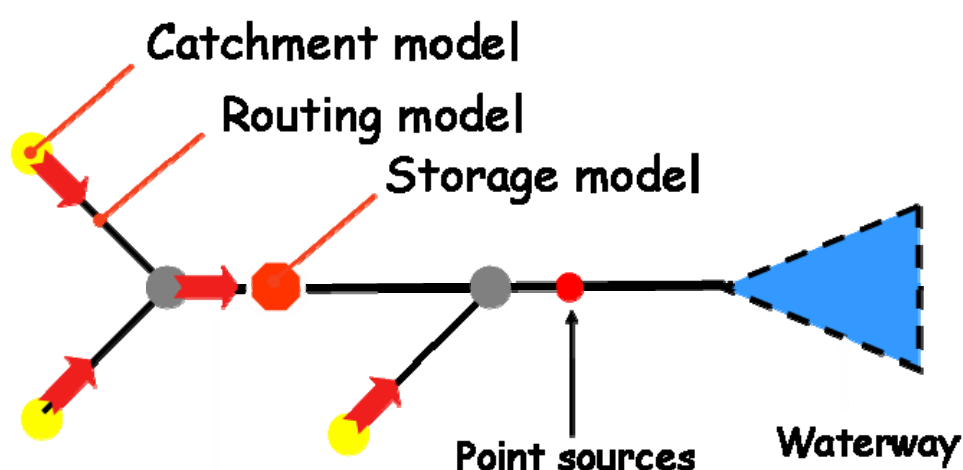


Figure 4 The linked submodels of EMSS.

The EMSS was developed for application in the Brisbane River catchment of South East Queensland and has been subsequently applied in several other Australian catchments.

4.3.4 E2

E2 is a catchment-scale modelling framework that can be used to predict the effects of land use change on the yield of water, nutrients and other contaminants (www.toolkit.net.au). It is designed to allow modellers and researchers to construct models by selecting and linking component models from a range of available choices. E2 enables a flexible modelling approach, allowing the attributes and detail of the model to vary in accordance with modelling objectives.

E2 is a development of the EMSS model (EMSS is described in Section 4.3.3). E2 includes all the capabilities of the EMSS model but with enhancements that enable better integration with other models. E2 predicts the hydrologic behaviour of large catchments. Like CatchMODS and EMSS, the E2 model structure is 'node-link' where sub-catchments feed into a node and water and material fluxes are routed down links. Catchments are typically broken into several to several hundred sub-catchments, interlinked by a river network of thousands to tens of thousands of kilometres in length. Gridded spatial data of elevation, land use and management, climate, geology and soils can be potentially linked to this spatial structure.

E2 is designed for researchers, modellers and consultants who are constructing tailored models for particular catchment management problems. In E2, the model structure and algorithms are not fixed. They are defined by the user, who can choose from a suite of available options. This affords much flexibility but algorithm selection and application requires the user to be familiar with the detail, applicability and data requirements of component models, and the implications of combining component models.

The building blocks of an E2 model are sub-catchments, nodes and links. The sub-catchment is the basic spatial unit in E2, although it can be divided into 'functional units' based on a common response or behaviour (e.g. based on landuse). Within each functional unit, three models may be assigned - a rainfall-runoff model, a constituent generation model and a filter model. Nodes represent sub-catchment outlets, stream confluences, or other places of interest (e.g. stream gauges, dam walls). Nodes are connected by links, forming a representation of the stream network. Links represent river reaches, dams, or floodplains. Within each link, three models may be assigned - a routing model, a source/sink model and a decay/enrichment model.

Currently, only generation rates-based approaches are available for use in E2. The first approach available in E2 is identical to the EMC/DWC approach used in EMSS. The second approach is a more simple non-hydrologic based generation rate applied to specified areas in a catchment typically delineated according to land use.

4.4 Comparison of models

Assessment of the strengths and limitations of modelling systems provides a useful basis to propose future directions for nutrient generation modelling. This section compares the various models described in the preceding section. Table 2 presents a summary of the features of the four models.

Table 2 Comparison of model features

Model feature	CMSS	CatchMODS	EMSS	E2
Time interval	Steady state	Steady state ¹	Daily	User specified
Spatial structure	Network	Node-link	Node-link	Node-link
Scenario investigation	Yes	Yes	Yes	Yes
Point sources	Yes	Yes	Yes	Potentially
Management costs submodel	Yes	Yes	No	No
In-stream ecological modelling	No	No	No	No
Embedded rainfall-runoff model	No	Yes	Yes	Yes
Embedded routing model	Yes	No	Yes	Potentially
Ease of application in new catchments	High	Medium	Medium-Low	Medium
Explicit uncertainty consideration	Yes ²	No	No	No

¹ The hydrologic submodel of CatchMODS operates at a daily timestep.

² Uncertainties in generation rates, the effectiveness of management practices for nutrient reduction and the cost of implementing management practices are considered.

4.4.1 Time interval

EMSS and E2 provide daily estimates of nutrient fluxes whereas CMSS and CatchMODS are limited to providing steady state estimates (reported as average annual loads). There are two main benefits to estimating nutrient fluxes on a daily time interval. Firstly, model outputs can generally be compared directly with measured concentration data and consequently ease assessment of model performance. Secondly, ecological response to changed nutrient fluxes can be more easily estimated with information at daily time intervals (Newham et al. 2005a). However, there are drawbacks associated with modelling nutrients at a daily time interval. These include firstly, raising the expectations of users with respect to the perceived predictive capabilities of nutrient generation models, secondly, significantly increasing the computing resources required to use these models, thirdly, requiring more onerous data inputs and finally, requiring additional interpretation of model outputs to communicate results.

Model developers and model users need to carefully balance these advantages and disadvantages with due regard to the objective of the modelling exercise they are considering.

4.4.2 Spatial structure

The CatchMODS, EMSS and E2 use a node-link spatial structure for catchment discretisation whereas CMSS uses a subcatchment network. Both structures allow for the effective routing of nutrients and reduces computing requirements over more distributed approaches (e.g. grid-based modelling). The disaggregation used in EMSS, CatchMODS and E2 is based on specified area-based thresholds to define the structure of catchment drainage systems. For catchment-scale applications, node-link discretisation provides a convenient approach. However, consideration needs to be given to the size of the individual subcatchment elements. A balance needs to be struck between the number of subcatchments that can be modelled and their corresponding size.

4.4.3 Scenario investigation

All four models have the facility to generate basic scenarios of catchment management change. Table 3 summarises the management changes that can be simulated by each of the models.

Table 3 Management simulation capabilities of the CMSS, CatchMODS, EMSS and E2 modelling systems.

Management change	CMSS	CatchMODS	EMSS	E2
Land use	Yes	Yes	Yes	Yes
Riparian stabilisation	Yes ¹	Yes	Yes	Yes
Gully management	Yes	Yes	No	Potentially
Riparian buffer zones	No	No	Yes	Yes ²
Water allocation	No	No	No ³	Potentially
Point sources	Yes	Yes ⁴	Yes ⁴	Yes
Climate scenarios	Yes ⁵	Yes	Yes	Yes

1 Provided stream length is specified.

2 Via Riparian Particulate Model (RPM), output of Riparian Particulates Working Group.

3 Simple reservoir operation only, no extractions considered.

4 Annual loads only.

5 Achieved by using a different set of generation rates; often used to look at range of dry average wet climate scenarios.

Land use change can be simulated in all models. In EMSS and E2, users have the facility to build different spatial patterns of land use with embedded GIS style tools. In CMSS, land use change is simulated by converting areas (or percentages) of existing land use according to user-defined rules e.g. 'convert 100% of grazing areas to peri urban use'. In CatchMODS, land use changes are simulated by specifying the proportions of the different land uses at a subcatchment level. The latter two approaches have several advantages. Firstly, they enable construction of simpler user interfaces. Secondly, they reduce the perceived level of complexity for users. Finally, they manage expectations concerning model accuracy. The primary advantage of simulating spatially explicit land use changes is it enables improved representation of the effect of spatially dependent land use changes on nutrient fluxes e.g. riparian buffer establishment.

In general terms, the simulation of linear management changes, for example, in gully and riparian zones, are not well simulated by the models described in this report. Important riparian and gully management processes are modelled in a generally empirical manner. In CatchMODS, for example, increases in gully and riparian vegetation reduce nutrient source inputs by fixed proportions of base case estimates only and the trapping efficiency of near-stream vegetated areas is not explicitly considered. In the EMSS and CMSS, assignment of a riparian zone to a length of stream reduces sediment and nutrient input in proportion to the loading rate (dynamic in time in the case of EMSS). Deficiencies in simulation of riparian vegetation have been partially overcome with the embedding of a model of riparian particulate trapping (RPM) in E2, see Newham et al. (2005b). Continued improvement of the simulation of linear management changes is suggested as a focus for ongoing research.

The effects of changing water allocation and trading policies on stream hydrology is not explicitly considered in any of the models described in this report. While this is a gap, it maintains the overall complexity of models at a reasonable level. A possible way to consider the influence of different water allocation policies and management on nutrient generation, explicitly, is to use outputs from water allocation models (e.g. Letcher, 2001) as direct hydrologic inputs to nutrient generation models. In this instance careful consideration must also be made of the effect of water extractions on nutrient fluxes.

Each of the four models allow, or potentially allow, for user-specified point source nutrient inputs to be considered. This is a very useful feature and it should be retained for the development of future nutrient modelling. The models also allow for the simulation of the effects of a variety of climate scenarios on nutrient loadings. Again this is a useful feature which should be retained and enhanced in future modelling.

4.4.4 Hydrologic modelling

To develop reliable estimates of nutrient loading, streamflow information which reproduces both the volume of streamflow and also the distribution of flow across the simulation period is needed (Newham, 2003). EMSS, E2 and CatchMODS include embedded rainfall-runoff models in their structure. The embedded rainfall-runoff models drive many of the nutrient generation processes that are represented in those models. The rainfall-runoff models are based on SIMHYD for EMSS and IHACRES for CatchMODS. In E2 a selection of models are available for users to choose to suit the particular goal of their application. Users of rainfall-runoff models should consider the need for calibration and testing of rainfall-runoff model outputs as part of the process of model development.

4.4.5 Ease of development

To broadly improve the focus of management intervention nutrient generation models need to be easily applied in new catchments. The CatchMODS model has generally modest data inputs that can be easily imported for application in new catchments. As a result it is potentially more easily reapplied than the EMSS. The ease of application of CMSS is even higher. An advantage of CatchMODS is that it requires minimal software support and the underlying model code can be modified by non-expert programmers, CMSS, EMSS and E2 require software support for modification to any of the underlying models.

5 DIRECTIONS FOR NUTRIENT GENERATION MODELLING

Catchment managers and policy makers are increasing their reliance on the outputs from contaminant cycle models. Accordingly, the need for robust, credible and reliable tools is increasing. This report has sought to guide the ongoing development of nutrient generation approaches to ensure that future needs are well met. A comparison and evaluation of four catchment-scale models (CMSS, CatchMODS, EMSS and E2) in terms of their nutrient generation characteristics has been made. The four models described in the report meet the necessary requirements for supporting catchment management activities and as such provide a useful basis for evaluating future directions in nutrient generation modelling. The strengths and limitations of these models has been assessed and used to produce a series of recommendations for ongoing model development. In summary, it is suggested that development be directed towards scenario based assessment using models with node-link spatial structures, operating at daily time intervals. Such models need to be easy to use and adapt for application in new catchments and possessing of strong visualisation features for effective application by, and communication to, end-users. The future development of such a model will provide a robust basis for improving land and water management outcomes.

This review has linked current knowledge of N and P generation with future needs for catchment models. Although there are a limited number of published Australian studies on nutrient export rates, further research on the effect of land use on nutrient generation, down-stream nutrient assimilation and subsequent water quality within large catchments is needed. We have also discussed the assumption that uniform nutrient generation rates used in some catchment models may not always be appropriate, given that management practices vary considerably within land uses.

International and local studies show that surface and subsurface pathways and soluble nutrient components are important considerations when evaluating TN and TP losses under various land uses. Although such information is seldom used in Australian catchment models, its incorporation into catchment models would be particularly valuable. Some catchment models do not adequately include intensively farmed land use, management and the different forms of nutrients, with the subsequent likelihood of either underestimating nutrient losses, or potentially overestimating effectiveness of riparian buffers.

5.1 Surface and subsurface sources and pathways

The nutrient generation processes review, presented in Section 3, described a variety of surface and subsurface nutrient sources and pathways. Many processes needed to be considered and their importance varied considerably amongst the studies presented. Future nutrient generation modelling should account for all such processes. However, modelling of individual processes need not be explicit. A suggested starting point is to model surface and subsurface processes separately. This may be achieved via simulation of nutrient generation from predominantly erosion sources (hillslope and channels) and the separate simulation of groundwater- and soil drainage-related processes. Perhaps the simplest approach is to estimate nutrient loads by linking (i) observed sediment-particulate nutrient concentrations and sediment fluxes and (ii) observed groundwater nutrient concentrations to groundwater flows.

The incorporation of surface- and subsurface- nutrient generation processes is feasible in process-based models but slightly more problematic in generation rates-based models. CatchMODS incorporates both surface and subsurface pathways for simulation of N loads. EMSS and E2, to a lesser extent, enable generation rates (represented by EMC/DWC) for nutrient generation. In EMSS and E2 it is impossible to model interactions between contaminants (e.g. sediments and nutrients). However, the importance of particulates in nutrient generation warrants ongoing research to address this shortcoming.

5.2 Management practices

The effects of management practices in agricultural areas, e.g. fertilizer and effluent application rates, were identified as potentially important determinants of nutrient generation. The future development of nutrient generation models should aim to produce models which are able to simulate these processes. However, to achieve acceptable simulation of management practices, improved understanding and quantification of the effects of common management practices is needed. This can only be gained through experimental research.

5.3 Incorporation with hydrologic information and models

The importance of the effects of hydrologic factors on nutrient exports was highlighted in the nutrient generation review. Because of this dependence, nutrient generation models more closely linked to hydrologic models or data are suggested. In particular, nutrient generation models with sensitivity to rainfall and runoff producing events is required. The embedded rainfall-runoff models in CatchMODS, EMSS and E2 provide useful examples of linking hydrologic and nutrient generation modelling approaches.

5.4 Can generic nutrient generation models be developed?

The nutrient generation processes review identified the large variations in the magnitude (and presumably the underlying processes) of N and P generation across sites in Australia. Given this variability, it is difficult to use a single nutrient generation approach in all situations. For the selection of an appropriate modelling approach consideration needs to be given to factors such as:

- the objective of the modelling (including consideration of user requirements);
- the availability of data;
- the availability of resources;
- time available for model development; and
- the scale of model application.

Over time, generalities from models tailored to specific applications can be sought. We suggest that this is a far better approach than attempting to impose an existing off-the-shelf model without careful consideration of its capabilities and its application potential.

The importance of moving research from detailed plot to catchment scale, or from site-specific models to generalisations applicable at catchment scales has been emphasised by Davis and Koop (2006) and McDowell et al. (2004).

5.5 Access to water quality data

Modelling of nutrient generation is often severely constrained by a lack of water quality data. Access to water quality data is needed to build understanding of nutrient generation processes and also to enable calibration and testing of models. Without water quality data of sufficient spatial and temporal resolution, the construction of models is severely constrained.

Even when simple models are used for estimation of nutrient loads, collection of data on climate, flow and nutrient concentration is recommended for at least a few years (Letcher et al. 2002). Monitoring programs ideally should include nested stream gauges to allow in-stream processes to be understood, well distributed climate stations, and high temporal frequency monitoring to better understand nutrient generation during rainfall and runoff producing events (Letcher et al. 2002).

Collection of water quality data is a potentially expensive process and due regard must be given to the uses of collected data, including for modelling purposes. Routine monthly water quality monitoring often does not capture large runoff events which may carry a large percentage of the load (Baginska et al. 2003; Hunter et al. 1996). Event-based sampling is suggested.

5.6 Model frameworks

Flexible model frameworks such as E2 are potentially powerful tools to enable tailored simulation of the nutrient generation processes. They can facilitate catchment-scale modelling from simple screening approaches implemented via generation-rates based approaches to more complex process- and physics-based approaches. However, flexible model frameworks also have high potential for misuse i.e. application and linking of models outside the conditions for and situations for which they were developed. Users of flexible model frameworks such as E2 require considerable knowledge and experience with integrated catchment modelling to avoid their misuse.

5.7 Model user needs and expectations

It is critical that nutrient generation models meet user needs and expectations. This report focuses on the technical aspects of nutrient generation model development only but it is an equally important research challenge to construct the models such that they are relevant to the planning and decision-making environment. This requires close interaction with policy makers, analysts and catchment managers to establish how and when they may use such models and what features support and/or inhibit that use. The involvement of end-users is an important and necessary activity for the construction of effective models (Newham et al. 2004a).

It was found that end-users of models seek an ability to simulate effects of land use change, management of riparian zones, flow management and point source control (Newham et al. 2004a). Model users also wished to apply models over a range of scales, communicate results effectively and estimate uncertainty of results. Of note is that catchment managers ranked riparian zone management as the most important. However, the need for adequate simulation of riparian zone and in-stream nutrient processing has been deficient in many catchment models (Rutherford et al. 2003).

5.8 Improving generation rates-based approaches

Generation rates-based models are appealing because they are inexpensive, easy to implement and the results can be directly linked to land use (McNamara and Cornish 2005). However, confidence in the outputs of generation rate-based modelling can be limited by a shortage of locally-relevant nutrient generation rates, inadequate land use data, and the fact that generation rates-based modelling fails to take account of hydrologic factors that determine both the nutrient export and the delivery of nutrients to the receiving water (McNamara and Cornish 2005).

There is considerable evidence in USA, Europe, and more recently in New Zealand indicating that as soil P concentrations increase, the P concentration in overland flow increases. This is a potentially important component of nutrient delivery to waterways downstream of intensive land use such as dairying. Soil testing for P is commonly practiced to enable establishment of soil fertility for crop or pasture requirements. However, agronomic soil tests commonly measure plant-available P but do not include the potential for environmental loss to waterways (McDowell et al. 2002). Recent research has focused on developing relationships between soil test P and dissolved P in surface runoff or other extracts. Factors enhancing P loss relative to soil concentrations include soil texture, particularly sandy soil, P retention, waterlogged soils where P may be mobilised, and soil P levels above plant requirements (McDowell et al. 2004).

Such relationships are commonly linear or split-line (McDowell and Trudgill 2000; McDowell et al. 2002). For example, McDowell and Trudgill (2000) showed that as soil Olsen P level increased above 31 mg/kg the $\text{CaCl}_2\text{-P}$ increased at a greater rate than below. Such soil P levels were greater than agronomic requirements. Using rainfall simulators, it has been shown that as soil Olsen P increases, the risk of increased DRP or TP concentrations in overland flow increases (McDowell and Condron 2004; McDowell et al. 2003). DRP levels in overland flow were generally greater in less weathered soils than more weathered ones, although the soil Olsen P level varied from 5–51 mg/kg where DRP in runoff exceeded 0.02 mg/L where it is considered eutrophication is likely to occur (McDowell et al. 2003). However, some of these studies have been conducted under non-field conditions. Consequently, changes that are likely to occur to soil physical properties such as compaction and reduced infiltration under grazing should be considered (Drewry et al. 2004).

It is well established by field experimentation for crops or pastoral conditions, for example in New Zealand, that it is unnecessary for farmers to apply P fertiliser above the agronomic soil optimum as this can contribute to potential losses to waterways (Monaghan et al. 2003). However, on-farm practice suggests agronomic soil optimums are often exceeded in intensively farmed areas, with subsequently risk of greater P loss to waterways (Drewry et al. 2003; McDowell et al. 2004). In New South Wales, overall farm P loss (1.4 kg P/ha/year) on dairy farms was considered satisfactory, although the loss was greater on effluent-applied areas, which was also associated with greater soil Olsen P levels (Drewry et al. 2005).

Not only is the risk of P loss more likely under high soil P levels under intensive farming, there is also considerable evidence from Australian research showing that large proportions of P in overland flow are DRP or soluble P under dairying (Cornish et al. 2002; Fleming and Cox 2001). Nash and Murdoch (1997) showed that 93% of annual P lost in overland flow was in dissolved form, even though soil P was moderate (Olsen P 29 mg/kg), while other studies indicate varying proportions of soluble to TP (Cornish et al. 2002; Stevens et al. 1999). In contrast, the South Australian study of Cox and Ashley (2000) showed that catchment discharge contained 100% dissolved P. Several of these studies in south-eastern Australia highlight the importance of dissolved P in groundwater

discharge and overland flow. Such studies have implications for riparian buffer management as riparian buffers are unlikely to reduce P losses from intensive agriculture in these situations.

Ideally, only the surface runoff or quickflow component of streamflow contribution should be used to scale nutrient generation rates (McNamara and Cornish 2005). However, in practice accurate estimation of surface runoff is very difficult especially at catchment scales. This is due to a range of factors including the generally poor coverage of rain gauges.

These factors and others discussed in this review will help guide the ongoing development of future of nutrient generation and catchment modelling needs.

6 GLOSSARY OF NUTRIENT TERMS

Term	Definition
Ammonium	A form of nitrogen, namely NH_4^+ .
$\text{CaCl}_2\text{-P}$	Calcium chloride extractable P, used for extracting soil P (McDowell and Trudgill 2000).
Dissolved reactive P (DRP)	DRP, or filterable P, is commonly measured by passing through a 45 μm filter and colorimetry. This can include P attached to very fine soil colloids which pass through the filter (McDowell et al. 2004; Nash et al. 2002). A generally equivalent established term is orthophosphate. However, "reactive P" has been suggested based on specific chemical reagents and colorimetry. The issue is discussed further in Haygarth and Sharpley (2000).
Interflow	Lateral water flow below the soil surface (Haygarth and Sharpley 2000).
Leaching	The removal of minerals and compounds from the soil by percolating water. Commonly refers to vertical soil water movement, although leaching is actually a process, rather than a hydrological pathway per se (Haygarth and Sharpley 2000).
Macropore flow	Soil water movement but via large soil pores.
Mineralisation	Conversion of organic forms of nutrients into inorganic or mineral forms (Cameron and McLaren 1996).
Nitrate	A form of nitrogen, namely NO_3^- .
Nitrification	Soil process where ammonium in soil is converted to nitrate.
Olsen P	A soil test for plant available P.
Overland flow	Movement of water exclusively over the soil surface during heavy rain (Haygarth and Sharpley 2000).
Particulate P (PP)	Commonly refers to P that does not pass through a 45 μm filter.
Soil nitrogen	Nitrogen forms in soil, made up of predominantly (i) organic compounds, (ii) ammonium held by clay particles, and (iii) mineral forms including ammonium, nitrite and nitrate in soil solution (Cameron and McLaren 1996).

Soluble or dissolved P	Common term for filterable P, commonly measured by passing through a 45 μm filter.
Surface runoff	Lateral movement of water from land, above and below the soil surface, which causes short term increase in flow at the catchment outlet (Haygarth and Sharpley 2000).
Total phosphorus (TP)	A filtered and unfiltered sample subjected to a digestion for TP yields total dissolved P (TDP) and TP, with particulate P (PP) calculated as the difference between TP and TDP (McDowell et al. 2004).
Total nitrogen (TN)	Total N includes all forms of N including organic-bound and inorganic forms (e.g. nitrate).

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