An Index-Based Modelling Approach to Evaluate Nutrient Loss Risk at Catchment-Scales

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ABSTRACT

This paper presents an approach to evaluate phosphorus loss risk to waterways using index-based modelling at the large catchment scale. Index-based approaches are used to identify areas of greatest nutrient source strengths, and so called 'critical source areas' of nutrient loss risk. Compared with more sophisticated water quality modelling approaches, index-based approaches are less likely to be constrained by a lack of input data and provide good spatial representation of catchment source strengths, although they do not represent nutrient generation processes explicitly.

In this research, soil regolith source and transport risk factors such as soil P concentrations, soil P sorption, soil map information, land use, erodibility, texture, and catchment-scale hydrology are used. The research is designed to help evaluate source strengths and transport risks to assist managers to improve the focus of remediation actions to reduce nutrient delivery to waterways. This paper presents a case study of index-based modelling in the 1810 km^2 Tuross River catchment of coastal southeast Australia. Predominant land uses are conservation and production forests, national parks, cattle grazing, dairy production and urban expansion. Knowledge of potential sediment and nutrient losses in the region is poor and so the index-based approach is a useful one to prioritise sources and resources.

Development of the P index in the Tuross River catchment (Figure 1) shows the majority of the catchment (67%) area is considered to have a very low or low risk of P loss. A P index <2.4 is considered low risk, while a P index 2.4–5.4 is considered moderate risk. The proportion of the catchment area of moderate P loss risk was 32.9%, while the high risk area was 0.03%. Management should be directed firstly to areas of high risk to reduce losses, although this should be implemented with knowledge of the costs of managing different areas and source strengths.

Nutrient indices such as the type developed and applied here are complementary to other modelling approaches. The index approach generally provides much more detailed spatial resolution than fully- or semi-distributed modelling approaches. Semi-distributed models such as CatchMODS and SedNet/ANNEX can be used to set priorities at a broader catchment scale and they assist in the quantification of pollutant fluxes and simulation of broad management changes. Such changes could include conversion of areas from forestry to intensive land use. Index approaches are however potentially more relevant to the spatial level at which management changes, and particularly changes in farming systems, are applied i.e. the paddock and small subcatchment scale. In this way semi-distributed models can be combined with index approaches to provide a set of powerful tools to influence management outcomes. Semi-distributed models can provide overall direction to set the broad focus of management and index approaches can then be used to refine on-the-ground investigations and investment priorities.

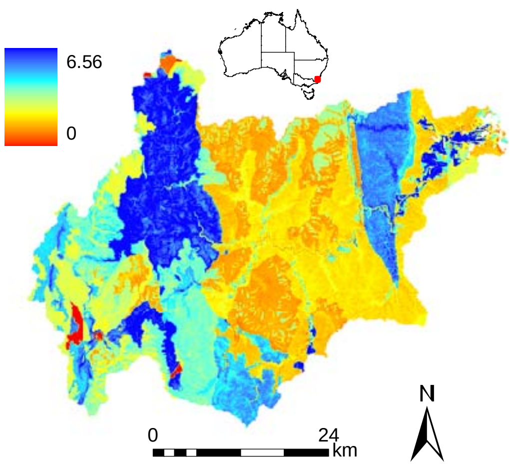

Figure 1. The Tuross River catchment P index. See text for interpretation.

INTRODUCTION

Assessing the potential risk of pollutant loss to waterways is essential for effective planning of control strategies, and hence avoiding potential problems of eutrophication. A range of modelling techniques are available but they differ in their approaches. Complex models may suffer from lack of readily available input data and error accumulation, while simple models may predict equally as well or better than complex models (Drewry *et al.* 2006; Merritt *et al.* 2003; Newham and Drewry 2006). Models can assist managers to evaluate the likely source strengths and impacts of land use and management on the long-term nutrient export status of catchments.

The combination of soil regolith properties and transport factors combine to determine the overall soil and diffuse source nutrient losses to waterways. Some factors affecting soil erosion include overland flow and subsurface pathways, connectivity to waterways, the extent of gully and stream bank erosion, and soil regolith physical and chemical factors (Greene and Hairsine 2004; McDowell *et al.* 2004).

To address nutrient-related water quality issues, a range of index-based models are in use. Index-based approaches are used to identify areas of greatest nutrient export or critical source areas (Heathwaite *et al.* 2000; McDowell *et al.* 2002). Such techniques have been applied for nutrient management in United States and Europe. The P index has been modified for use in New Zealand at paddock and farm scale (Hart *et al.* 2002; McDowell *et al.* 2005). 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 (McDowell *et al.* 2005; Sharpley *et al.* 2003). Source factors may include soil nutrient levels and fertiliser management. Transport factors include erosion, leaching, runoff and the connectivity to the waterway.

Index-based approaches were originally developed to predict risk of P loss at the field-scale (Sharpley *et al.* 2003) but were not designed to predict actual P loss *per se*. They have been used predominantly at field, farm scale or in small catchments (Heathwaite *et al.* 2000; McDowell *et al.* 2002), and are less likely to be constrained by a lack of input data than other models. Index-based models provide very good representation of catchment source strengths, but do not provide direct quantification of nutrient movement (Newham and Drewry 2006).

Some index concepts have been applied in Australia. For example, Newham *et al*. (2002) used an index approach in the Ben Chifley Dam Catchment to help identify potential sources and transport pathways of diffuse nutrients and prioritise management. Newham *et al.* (2002) increased the scale of application from previous studies by approximately three orders of magnitude. Modifications were made to improve the representation of connectivity through incorporating explicit gully erosion pathways. An index approach has recently been developed in Victoria to estimate risk of nutrient loss at paddock-scale (Melland *et al.* 2007).

This paper presents an approach to develop an index risk-based model using catchment-scale conceptual modelling with soil regolith factors, soil map and landscape information, land use, and catchment hydrology. A case study in the Tuross River catchment is presented. Risk of P loss is demonstrated by the Tuross River catchment P index. Knowledge of diffuse sediment and nutrient sources in the region is poor (DECC 2007), so this approach will lead to improved diffuse source knowledge and interpretation for improved catchment management. The research contributes to linking disciplines. The opportunities for closer integration of index based and conceptual models are also discussed.

TUROSS RIVER CATCHMENT CHARACTERISTICS

The Tuross catchment (1810 km^2) is located approximately 350 km south of Sydney, in south east Australia. The majority of the catchment is covered by native forest in rugged terrain. The flat or undulating coastal land surrounding the rivers and estuaries is used for agriculture, particularly beef cattle grazing. Dairy production in the Tuross catchment is predominant on moderately sloping land and floodplains. In the Tuross estuary, oyster farming, recreation and tourism are important to the local economy. The Tuross estuary has a complex array of lakes and channels formed behind a coastal sand barrier. With some exceptions, water quality is generally good (Haines and Wilson 2005), but this assessment is based on limited data with little information on the quality of water entering the estuaries during storm events. The catchment is an important source of urban drinking water for the Eurobodalla Shire Council. The long-term annual average rainfall in coastal areas of the catchment is approximately 1000 mm (Bureau of Meteorology data).

Table 1 Transport factor loss ratings and factor weights for the Tuross River catchment P index.

	Factor weight	Very low risk	Low risk	P loss rating Moderate risk	High risk	Very High risk	Reference
Risk value		0.2	0.4	0.6	0.8	1.0	
Soil erosion (Mg ha^{-1} yr^{-1}) [A]	1.5	<3	3–5	5–7	7–10	>10	
Contributing distance (m) [A]	1.0	>60	60–40	40–25	25–15	<15	
Slope (degrees) [A]	0.5	<3	3–5	5–7	7–10	>10	
Dispersion (%) for gully erosion	1.0	0-6	6–30	30–50	50–65	65–100	Tulau (2002)
Overland flow risk with Ksat (mm d^{-1})	0.5	>2880	1441–2880	481–1440	240–481	<240	Interpreted from Tulau (2002)
Texture rating for overland flow risk	0.5	Sand	Loamy sand to sandy loam	Loam to silt loam	Clay loam to silty clay loam	Clay	
Texture rating for leaching risk	0.5	Clay	Clay loam to silty clay loam	Loam to silt loam	Loamy sand to sandy loam	Sand	Heathwaite *et al.* (2000) Tulau (2002)
Leaching risk using CEC ($cmol_c$ kg^{-1})	0.5	>40	25–40	12–25	6–12	<6	Interpreted from Tulau (2002) and DPI (2005)

[A] Continuous variable

Table 2 Source factor loss ratings and factor weights for the Tuross River catchment P index.

	Factor weight	Very low risk	Low risk	P loss rating Moderate risk	High risk	Very High risk	Reference
Risk value		0.2	0.4	0.6	0.8	1.0	
Bray P soil content (mg kg^{-1})	1.5	<5	5–10	10–20	20–25	>25	Tulau (2002)
Olsen P soil content (mg kg^{-1})	1.5	<12	12–17	18–25	25–35	>35	Interpreted from (DPI 2005)
P loss risk from P sorption (mg kg^{-1})	0.75	>600	400–600	250–400	125–250	<125	Interpreted from Tulau (2002)
P loss risk from PBI	0.75	300–600	200–300	100–200	50–100	<50	Interpreted from DPI (2005)
P fertiliser application (Tuross River whole farm average) (kg P ha^{-1})	0.5	<10	10–20	20–40	40–50	>50	Drewry *et al.* (2005), unpub. & adapted from Melland *et al.* (2007)

MODEL INPUTS

Soil information

Soil landscape units were used in the index approach, as they are areas of land that "have specifiable topographies and soils that are capable of presentation on maps"(Tulau 2002). The soil landscape concept permits the integration of both soil and landform constraints into a single mapping unit with similar soil characteristics affecting land use (Kovac *et al.* 1989; Tulau 2002; Tulau 2006).

Much of the Tuross River catchment soil analyses and some interpretive information were obtained from DNR from both published (Cooma and Narooma sheets) data and reports (Tulau 1994; Tulau 2002) and unpublished (Cobargo sheet) soil data (Tulau 2006). The data had been collected for soil landscape mapping, so sampling densities were appropriate for the scale of mapping (1:100000). Mapping at such scales is sufficient for regional perspectives, broad land management and to gain understanding of soil properties (Tulau 2002).

A number of soil measurements were used in this research. Detailed methods are available elsewhere (Tulau 2002). Soil measurements included particle size analysis, saturated hydraulic conductivity, cation exchange capacity (CEC), USLE soil erodibility factor (K), dispersibility of the fine fraction and clay content, and soil P concentrations. Further samples, measurements and management information were collected from dairy farms in the Tuross River region (Drewry *et al.* 2005).

Landscape and management information

All DEM, land use, soil mapping and other GIS data were re-projected to a uniform projection. Details of source and transport factors used in the Tuross River catchment P index, with rankings and weightings, are presented in Tables 1 and 2.

MODELLING METHODS

For the Tuross River catchment P index modelling, source and transport *factor loss ratings* are ranked (e.g. from very low to very high risk), and then *factor weightings* assigned to the particular factor when calculating the overall index. Factor loss ratings and factor weightings suitable to the Tuross River catchment or large catchment-scale (Newham *et al.* 2002) were applied. Alternatively, values were adapted from literature values.

Loss ratings and weightings applied reflect likely source areas and the sediment source-limited hysteresis pattern in observed event-based water quality data (data not presented). Some source factors are therefore more highly weighted than some transport factors in the Tuross River catchment P index. Similarly, for this catchment, factors associated with quantity of soil erosion also have a high weighting. A risk loss ranking of 0.2–1.0 was used as it is likely that in many cases, source and transport factors will contribute to nutrient loss at some time, rather than be zero. Based on catchment water quality observations (e.g. Drewry *et al*. 2005 and unpublished data), factors associated with erosion and sediment loss were weighted more highly in the Tuross River catchment P index than in the Tuross River catchment N index (not presented). Source factor data for dairying and intensive land use areas were developed as a separate data layer because several soil-related aspects were considered land use-related rather than related to the greater area of a natural soil landscape feature.

To reflect connectivity in the index models, a distance-based measure of connectivity was included. The distance of pollutant-producing areas from a stream was estimated through analysis of DEM data with a FORTRAN-coded program. Several spatial data inputs to the index e.g. slope and hillslope erosion retained their continuous nature in the index. These variables were modified using simple non-linear functions to match the required range of values for use in the index. The decision to use continuous rather than discrete values reflects the nature of the data and the desire to have index values spread across a continuum of values from high to low risk where possible.

The Tuross River catchment P index was calculated using GIS AML programming. Source and transport factors were additive, with the final index calculated as multiplicative for total source and transport factors.

RESULTS

This section presents results for the Tuross River catchment P index (Figure 1). The P index in the eastern part of the catchment is shown in Figure 2 in more detail. Using the factor loss ratings, weightings and calculation of the index, the maximum potential P index was 15.1. For interpretation purposes, a P index <0.6 is considered very low risk, and 0.6–2.4 is considered low risk, with low impacts on water quality likely. A P index of 2.4–5.4 is considered moderate risk, indicating some management actions should be taken to minimise losses to waterways. A P index >5.4 is considered high risk, with adverse impacts on water quality likely. These are areas where soil and water management actions could be taken to reduce losses.

The index results show the majority of the catchment (64.9%) area is considered to be low risk, while 2.1% of the area is very low risk. The proportion of the catchment area considered to be moderate risk was 32.9%, while the high risk area constituted 0.03% (Table 3). The maximum actual P index was 6.6.

Results from the P index indicate that soil landscapes in the catchment that have generally moderate risk of P loss including for example, the Jillicambra and Yellow Pinch soils. The Jillicambra soil landscape has moderate risk for the source factors P concentration and P sorption. The Murrah soils have very low mean P concentrations coupled with high P sorption, resulting in low source risk. Ranges of soil (0–10 cm depth) property input values for different soil landscape in the catchment, for example, were 1–33 mg kg^{-1} for Bray P soil content. P sorption was 100–812 mg kg^{-1}. Dispersion percentage ranged from 7–60%.

The Tuross catchment P index indicates that transport factors were particularly influential in steep areas and near waterways. While this is an obvious observation, it is the linkage of this with the source from the index that assists identification of options for prioritising management. For example, in dairy land use areas in the east of the catchment, the total transport factor was generally low to moderate risk, but the total source factor (such as soil P concentration) was moderate to high risk. Results show the risk of P loss from dairy land use in the east of the catchment (Figure 2) was generally considered moderate, with P index values commonly >3.9, but with only a small area of high risk (up to 5.4–6.4) generally within 30 m of waterways. Management on farm should therefore be directed to reducing source risk in close proximity to waterways.

Spatial contribution of the total source factors, over the whole Tuross River catchment, contribute less risk than the total transport factors. This is demonstrated in Table 3 by the percentage area of total source factors being very low to low risk (82.6%), compared with total transport factors being very low to low risk (31.7%). Consequently, transport risk factors are likely to contribute greater risk than some source factors, therefore, where practicable, should be targeted for reducing diffuse nutrient losses.

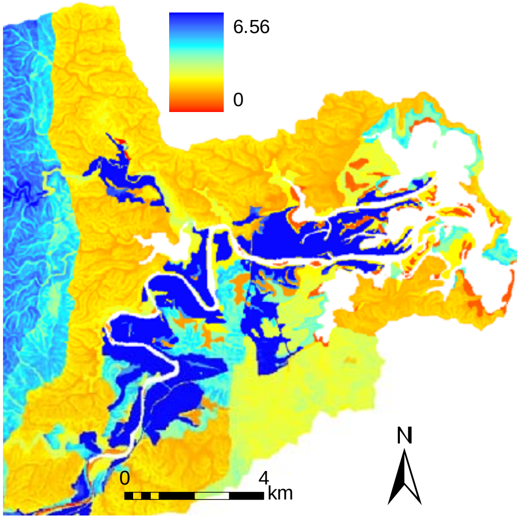

Figure 2. Detail of the Tuross River catchment P index in the east of the catchment. See text for interpretation.

Table 3 Spatial contribution (% of area) of Tuross River catchment for very low to high risk classes for P index, total source and transport factors.

Percentage area	Very low risk	Low risk	Moderate risk	High risk
P index	2.1	64.9	32.9	0.03
Total P source rating class	41.9	40.7	15.9	1.4
Total P transport rating class	1.3	30.4	66.8	1.5

Also of note is that there are also large areas of moderate risk in the west of the catchment (Figure 1), demonstrating that the P index results show that it is likely that diffuse P loss is from large areas of the catchment, rather than intensive land use only.

DISCUSSION

Knowledge of diffuse sediment and nutrient sources in the Eurobodalla region is generally poor (DECC 2007). The Tuross catchment P index in conjunction with complimentary aspects of this research, are valuable to gain knowledge of diffuse source strengths in this region, and to focus future research and management efforts.

In the Tuross catchment, management should be directed to areas where the index indicates potential nutrient loss is likely to be high. P loss risk may be greatest where both P source and transport factors are considered high and coincide, although this is a small area of a catchment. In extensive areas of large catchments, landscape features are potentially more important than management for determining risk (Newham *et al.* 2002).

Soil P levels should generally not be above agronomic targets, as there is likely to be a greater and unnecessary risk to waterways. Agronomic guidelines for grazed dairy pasture recommend soil (Olsen) P targets lower than some values from this research, although irrigated land in the Tuross River catchment appears generally well managed for nutrients. Although the Tuross River catchment N index is not presented here, N appeared to be well managed on Tuross dairy farms.

For the Tuross River catchment P index, the transport factors texture rating and CEC for leaching risk were used to reflect potential leaching risk of P through soil, particularly coarse textured soils, rather than assuming P moves only via overland flow on particulate material. A CEC greater than 10 $cmol_c\ kg^{-1}$, for example, is desirable to minimise P leaching (DPI 2005). As the ability of a soil to retain P increases (i.e., P sorption and PBI increase), there is less risk of drainage loss to waterways.

Some cautions with the approach in this research should be noted. There are issues when using the Universal Soil Loss Equation (USLE) or its variants to estimate hillslope erosion, such as not accounting for non-uniform slope erosion, sediment delivery to streams, gully erosion or floodplain deposition (Erskine *et al.* 2003).

Index approaches identify potential risk rather than actual risk, so some caution should be used when interpreting results. Broad scale models are useful when focussing on areas where practical and financial returns to mitigate risk of nutrient loss are greatest (Heathwaite *et al.* 2003). The index approach in this research has simplified some processes and landscape systems at large catchment scale, but as with other approaches, is useful to compare between areas, rather than to predict actual values (Sharpley *et al.* 2003), so is useful for evaluating management options.

Nutrient indices such as the type applied here are complementary to many other modelling approaches. The index approach generally provides much more detailed spatial resolution than fully- or semi-distributed modelling approaches. Semi-distributed models such as CatchMODS (Newham *et al.* 2004) and SedNet/ANNEX (Young *et al.* 2001) can be used to set priorities at a broader catchment scale and they ease quantification of pollutant fluxes and simulation of broad management changes. Index approaches are however, potentially more relevant to the spatial level at which management changes, and particularly changes in farming systems, are applied i.e. the paddock and small subcatchment scale. In this way semi-distributed models can be combined with index approaches to provide a set of powerful tools to influence management outcomes. Semi-distributed models can provide overall direction to set the broad focus of management, and index approaches can then be used to refine on-the-ground investment priorities.

CONCLUSIONS

This index approach in this research has been useful in improving understanding of nutrient loss in a large catchment, as there have been few studies developing index approaches at large catchment scale. This scale of development is used to provide a broad catchment perspective. As with many models, limitations of data and scale, however, should be considered when applying and interpreting the P index. The index model provides more specific information than other catchment-scale tools for evaluating nutrient risk loss. Many important aspects of soil and nutrient loss have been incorporated in the development and application of the model that would otherwise not be taken into account during the application of commonly available large scale catchment models.

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REFERENCES

DECC (2007), Workshop to inform the development of a NSW diffuse source water pollution strategy. Southern workshop report (Batemans Bay). Department of Environment and Climate Change, Sydney.

DPI (2005), Fertilising dairy pastures. A manual for use in the Target 10 soils and fertiliser program, Department of Primary Industries: Melbourne, Victoria.

Drewry, J. J., Newham, L. T. H., Greene, R. S. B., Jakeman, A. J. and Croke, B. F. W. (2005), An approach to assess and manage nutrient loads in coastal catchments of the Eurobodalla region, NSW, Australia, MODSIM 2005 International Congress on Modelling and Simulation, pp. 2658-2664, Melbourne.

Drewry, J. J., Newham, L. T. H., Greene, R. S. B., Jakeman, A. J. and Croke, B. F. W. (2006), A review of nitrogen and phosphorus export to waterways: context for catchment modelling, *Marine and Freshwater Research*, 57, 757-774.

Erskine, W. D., Mahmoudzadeh, A., Browning, C. M. and Myers, C. (2003), Sediment yields and soil loss rates from different land uses on Triassic shales in western Sydney, NSW, *Australian Journal of Soil Research*, 41, 127-140.

Greene, R. S. B. and Hairsine, P. B. (2004), Elementary processes of soil-water interaction and thresholds in soil surface dynamics: a review, *Earth Surface Processes and Landforms*, 29, 1077-1091.

Haines, P. and Wilson, J. (2005), Interpretation of water quality monitoring program results. WBM Oceanics Australia, Broadmeadow, NSW.

Hart, M. R., Elliott, S., Petersen, J., Stroud, M. J., Cooper, A. B., Nguyen, M. L. and Quin, B. F. (2002), Assessing and managing the potential risk of phosphorus losses from agricultural land to surface waters, Dairy farm soil management. Occasional Report No. 15., pp. 155-166, Palmerston North, New Zealand.

Heathwaite, A. L., Johnes, P. J., Fraser, A., Lord, E., Hutchins, M. and Butterfield, D. (2003), The phosphorus indicators tool: a simple model of diffuse P loss from agricultural land to water, *Soil Use and Management,* 19, 1-11.

Heathwaite, L., Sharpley, A. and Gburek, W. (2000), A conceptual approach for integrating phosphorus and nitrogen management at watershed scales, *Journal of Environmental Quality,* 29, 158-166.

Kovac, M., Murphy, B. W. and Lawrie, J. W. (1989), Soil landscapes of the Bathurst 1: 250000 sheet, Department of Land and Water Conservation: Sydney.

McDowell, R. W., Biggs, B. J. F., Sharpley, A. N. and Nguyen, L. (2004), Connecting phosphorus loss from agricultural landscapes to surface water quality, *Chemistry and Ecology,* 20, 1-40.

McDowell, R. W., Monaghan, R. M. and Wheeler, D. (2005), Modelling phosphorus losses from pastoral farming systems in New Zealand, *New Zealand Journal of Agricultural Research,* 48, 131-141.

McDowell, R. W., Sharpley, A. N. and Kleinman, P. J. A. (2002), Integrating phosphorus and nitrogen decision management at watershed scales, *Journal of the American Water Resources Association,* 38, 479-491.

Melland, R., Smith, A. and Waller, R. (2007), Farm Nutrient Loss Index. A nitrogen and phosphorus loss index for the Australian grazing industries. User manual. Department of Primary Industries, Ellinbank, Victoria.

Merritt, W. S., Letcher, R. A. and Jakeman, A. J. (2003), A review of erosion and sediment transport models, *Environmental Modelling & Software,* 18, 761-799.

Newham, L. T. H. and Drewry, J. J. (2006), Modelling catchment-scale nutrient generation. CSIRO Land and Water and The Australian National University, CSIRO Land and Water Technical Report 28/05. National river contaminants program of Land and Water Australia, Canberra.

Newham, L. T. H., Jakeman, A. J., Letcher, R. A., Heathwaite, A. L., Smith, C. J. and Large, D. (2002), Integrated water quality modelling: Ben Chifley Dam Catchment, Australia, Integrated Assessment and Decision Support, Proceedings of the First Biennial Meeting of the International Environmental Modelling and Software Society, pp. 275-280, June 2002.

Newham, L. T. H., Letcher, R. A., Jakeman, A. J. and Kobayashi, T. (2004), A framework for integrated hydrologic, sediment and nutrient export modelling for catchment-scale management, *Environmental Modelling & Software,* 19, 1029-1038.

Sharpley, A. N., Weld, J. L., Beegle, D. B., Kleinman, P. J. A., Gburek, W. J., Moore, P. A. and Mullins, G. (2003), Development of phosphorus indices for nutrient management planning strategies in the United States, *Journal of Soil and Water Conservation,* 58, 137-151.

Tulau, M. J. (1994), Soil landscapes of the Cooma 1:100000 sheet, Department of Conservation and Land Management incorporating the Soil Conservation Service of New South Wales: Sydney.

Tulau, M. J. (2002), Soil landscapes of the Narooma 1:100000 sheet, Department of Land and Water Conservation: Sydney.

Tulau, M. J. (2006), Soil landscapes of the Cobargo 1:100000 sheet. Department of Land and Water Conservation, Unpublished draft report, West Kempsey, NSW.

Young, W. J., Prosser, I. P. and Hughes, A. O. (2001), Modelling nutrient loads in large-scale river networks for the National Land and Water Resources Audit. CSIRO Land and Water, Technical Report 12/01, Canberra.