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Lachlan T. H. Newham

John J. Drewry

Baihua Fu

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# Catchment-Scale Water Quality Modelling and Integration of Collateral Information

**Lachlan T.H. Newham**[a], **John J. Drewry**[a,b,c] **and Baihua Fu**[a]

[a] *The Fenner School of Environment and Society, The Australian National University, Canberra ACT 0200, Australia (lachlan.newham@anu.edu.au)*

[b] *Cooperative Research Centre for Landscape Environments and Mineral Exploration, The Australian National University, Canberra, ACT, Australia.*[c] *Current address: Mackay Whitsunday Natural Resource Management Group*

**Abstract:** This paper describes progress on techniques in the modelling of sediments and nutrients to inform management effort. It describes a catchment-scale model known as CatchMODS, and the integration of knowledge from a range of collateral sources to inform its development and application. A full description of the model, including its hydrologic, sediment and nutrient modules, is presented. The paper describes how knowledge from field-based studies is incorporated to support the modelling. Knowledge is generated from: (i) water quality monitoring; (ii) sediment tracing of critical source areas and relative subcatchment contributions (using geochemical, and mineralogy techniques); and (iii) field investigation, particularly landscape measurement. This knowledge is used for model conceptualisation, correct parameterisation and performance testing.

***Keywords:*** Water quality modelling; collateral knowledge integration; water quality monitoring; sediment tracing.

## 1. INTRODUCTION

This paper describes progress on techniques of modelling sediment and nutrients to inform management effort. A catchment-scale modelling framework known as the Catchment-Scale Management of Distributed Sources (CatchMODS) model is at the core of a research program that integrates modelling and field assessment techniques. The latest structure and algorithms of the CatchMODS model are described along with efforts to inform the model development process through integration of collateral knowledge. The structure of the modelling framework is informed by studies of pollutant sources and fate processes. These studies, including monitoring, sediment tracing and field investigation, provide data for correct parameterisation and model performance testing. A discussion of the integration process is made and opportunities to improve the representation of pollutant processes are described.

## 2. CATCHMENT-SCALE MANAGEMENT OF DISTRIBUTED SOURCES MODEL

The CatchMODS model framework is designed to simulate current conditions and the effects of management activities on the quality of receiving waters at catchment scales (Newham et al. 2004). The framework integrates hydrologic, sediment and nutrient export models with a simple economics submodel, to enable the development and evaluation of the impact of management strategies for reducing nutrient and sediment yields to waterways. The model has been applied in several catchments for various management and research purposes. It was initially developed for application in the Ben Chifley Dam catchment of NSW and has since been applied in several other Australian catchments including the Avon-Richardson in north central Victoria and Cox Creek in the Adelaide Hills, SA.

CatchMODS is based on a series of linked river reaches and associated subcatchment areas. The modelling is lumped at these stream reach and subcatchment units (Newham et al. 2004). The topology of the stream network enables the downstream routing of pollutants with the individual submodels each simulating processes of pollutant attenuation and/or deposition. Reaches and subcatchments are disaggregated using an area threshold to define reaches. The topology of the stream network defines the associated subcatchment areas. The size of a subcatchment in a typical application of CatchMODS averages 30 km$^2$. Further details on the representation of spatial variability in the model and network topology are provided in Newham et al. (2004). CatchMODS is structured around its hydrologic, economic, sediment and nutrient export submodels which are described in the following sections.

## 2.1 Hydrology

The IHACRES rainfall-runoff model (Jakeman et al. 1990) is used to estimate both surface and subsurface discharge in CatchMODS. It is applied at a daily timestep with its temperature and rainfall inputs linearly scaled according to subcatchment mean rainfall and mean elevation, respectively. A full description of the IHACRES model and its regionalisation is outside of the scope of this paper but Post and Jakeman (1999) provide an example of the regionalisation of IHACRES.

The modelled daily discharge from the IHACRES model is used to generate several flow-related statistics for each subcatchment. The mean annual flow ($Q_{MAF}$) for a subcatchment is estimated as sum of the daily flows during the period of record divided by the number of days of record simulated. The bankfull discharge ($Q_{BF}$) is estimated as the flow corresponding to a specified average recurrence interval. For overbank flows ($Q_{OB}$), the median flow volume is used for flows greater than $Q_{BF}$. Baseflow volumes are estimated for each subcatchment using the baseflow filter method of Croke et al. (2001). The local baseflow volume is calculated for each subcatchment $i$

$$Q_{BF_{local},i} = Q_{BF,i} - \sum_u Q_{BF,u}$$

where $Q_{BF,i}$ is the baseflow from subcatchment $i$ ; and $\sum_u Q_{BF,u}$ is the sum of the upstream baseflow inputs. A similar approach is used to estimate $Q_{QF_{local},i}$ – the quickflow from subcatchment $i$. Scenarios of the impact of climate changes are implemented by substituting the climate inputs to IHACRES. Historic or stochastic inputs are used. The effects cascade through the modelling framework via the flow-related statistics.

## 2.2 Sediment

The sediment submodel of CatchMODS is substantially modified from the SedNet model (Prosser et al. 2001) but retains several of its underlying algorithms. The focus of CatchMODS is on the simulation of the suspended sediment (SS) fraction. This reflects the importance of SS as a source and transport medium for many common stream pollutants e.g. phosphorus. It also enables investigation of contemporaneous SS fluxes and management effects over the more historic perspective of SedNet. SS is defined as the less than 63μm diameter sized particle fraction. Sediment inputs are estimated from hillslope, gully and streambank erosion sources. Road-derived sediment inputs to a subcatchment are soon to be estimated via the WARSEM model (Dubé et al. 2004) with minor modifications made to that model to enable its inclusion in the structure of CatchMODS, see Fu et al. (2007) for an example of the application of the WARSEM model, and Fu et al. (submitted) for a review of road erosion modelling.

### 2.2.1 Hillslope erosion

Hillslope erosion is estimated via use of the RUSLE (Renard et al. 1997). The application of the RUSLE is lumped at the subcatchment scale to ease scenario construction. The combined rainfall ($R$), soil erodibility ($K$) and length and slope ($LS$) factors are estimated and multiplied on a cell-by-cell basis. A mean value of the combined factors is calculated for each subcatchment

$$\overline{\lambda}_i = \sum_{k=1}^{n} R_k K_k LS_k \bigg/ c$$

where $\overline{\lambda}_i$ is the mean value of the combined factors for subcatchment $i$; $k$ is the cell; and $c$ is the total number of cells in the subcatchment. The estimated hillslope erosion for each subcatchment ($H_i$) is the product of $\overline{\lambda}_i$, the subcatchment cover factor ($\overline{C}_i$) and a sediment delivery ratio (SDR), $R$ and the area of subcatchment $i$ ($A_i$)

$$H_i = \overline{\lambda}_i \overline{C}_i \times R \times A_i$$

$\overline{C}_i$ is estimated as

$$\overline{C}_i = \sum_j C_j A_j \bigg/ A_i$$

where $C_j$ is the crop factor for land use $j$; and $A_j$ is the area of land use $j$. A SDR scales the hillslope erosion estimate from the RUSLE to the quantity of sediment that is delivered to the stream network. The SDR takes a value between 0 and 1. In the application of CatchMODS in the Avon-Richardson catchment, a subcatchment-specific sediment delivery ratio is being trialled. Normalised indices of sediment transport based on Prosser and Rustomji (2000), Bhattarai and Dutta (2007) and Warren et al. (2005) are being trialled to scale subcatchment hillslope inputs. Management change scenarios that affect the hillslope erosion estimates are implemented via changes in land use proportions for each subcatchment. Land use changes are simulated via changes of the $\overline{C}_i$ value.

### 2.2.2 Gully erosion

Gully erosion is assumed to be sourced from erosion of the sidewalls of permanent gullies. The mass of sediment derived from gully erosion is estimated as the product of the volume of gully erosion and the bulk density of the eroded sediment. Gully erosion is broken into multiple categories to reflect differences in sediment production and physical dimensions amongst the gullies of a catchment. The estimated gully erosion for each subcatchment is

$$G_i = \sum_s E_{s,i} 2 r_s d_s \rho \varpi_g$$

where $E_{s,i}$ is the effective length of gullies of severity class $s$ in subcatchment $i$; $r_s$ is the annual average lateral erosion rate of gullies of severity class $s$; $d_s$ is the depth of gullies of severity class $s$; $\rho$ is the bulk density of eroded sediments and $\varpi_g$ is the proportion of suspended sediment in the eroded gully material. Management change scenarios are implemented via reducing the length of gully erosion for each severity class for subcatchments where gully erosion control works are to be implemented. An effectiveness factor is introduced to reflect the anticipated or measured effectiveness of the control works.

$$E_{s,i} = L_{s,i} - \nu L_{r,i}$$

where $L_{s,i}$ is the length of gullies of severity class $s$ in subcatchment $i$; $\nu$ is the effectiveness factor for the control works; and $L_{r,i}$ is the length of gully control works.

### 2.2.3 Streambank erosion

Streambank erosion is estimated using the algorithm of Prosser et al. (2001)

$$S_i = aQ_{BF}^b L_{r,i} d_r \rho \varpi_s \left(1 - L_{v,i} / L_{r,i}\right)$$

where $a$ and $b$ are empirical parameters; $L_{r,i}$ is the total stream length in subcatchment $i$; $d_r$ is the mean streambank height; $\varpi_s$ is the proportion of suspended sediment in the eroded gully material; and $L_{v,i}$ is the non eroding (vegetated) reach length.

### 2.2.4 Sediment routing and floodplain deposition

The estimation of sediment deposition onto the floodplain uses the algorithm of Prosser et al. (2001). Total sediment contributions to a reach are estimated as

$$X_{in,i} = H_i + G_i + S_i + X_{up}$$

Routing to the downstream subcatchment ( $X_{out,i}$ ) is estimated as

$$X_{out,i} = X_{in,i} - \left( \frac{Q_{OB,i}}{Q_{MAF,i}} X_{in,i} \left( 1 - \exp\left( \frac{-vA_f}{Q_{OB,i}} \right) \right) \right)$$

where $v$ is the settling velocity of sediment particles on the floodplain.

## 2.3 Nutrients

Dissolved and particulate nutrient fractions are simulated separately in CatchMODS. The P and N submodels of CatchMODS are identical in structure. A generation-rate-based or flow-based approach (or a combination of the two) may be used for the simulation of dissolved nutrients. The attenuation of dissolved nutrients though the system is simulated using a simple exponential function.

### 2.3.1 Particulate nutrient input

Particulate nutrient input to subcatchment $i$ is estimated as

$$P_i = h \sum HS_{i,j} C_j + S_i C_s + G_i C_g$$

where $h$ is a nutrient enrichment factor; and $C_j$, $C_s$, $C_g$ are the surface soil, bulk streambank and bulk gully nutrient concentrations, respectively. Samples for the determination of soil nutrient concentration are taken from the top 5cm of the soil profile. The $h$ factor is introduced to represent the effects of the preferential erosion and delivery of finer soil particles that have higher nutrient concentrations on the hillslope. The factor is applied across all subcatchments and land uses in the absence of knowledge of nutrient enrichment for each specific land use and soil combination.

### 2.3.2 Dissolved nutrient input

Dissolved nutrient input to subcatchment $i$ is estimated as

$$DN_i = (1 - A_{GR})(oQ_{BF_{local},i} + pQ_{QF_{local},i}) + \sum_j A_{GR} G_j$$

where $A_{GR}$ is the area of subcatchment modelled via a generation rates approach, $o$ is the baseflow dissolved nutrient concentration (g/mL); $p$ is the quickflow dissolved nutrient concentration (g/mL); and $G_r$ is the areal generation rate for land use $j$. The inclusion of a generation rate for specific landuses enables use of the model in areas where nutrient loss per unit area is likely to be much greater than would otherwise be estimated by CatchMODS algorithms e.g. in dairy farming areas. A generation rate for specific land uses also enables use of the model in areas where field-collected water quality monitoring data is unavailable for model parameterisation.

### 2.3.3 Nutrient routing

Nutrient routing includes an estimate of the attenuation of dissolved nutrients through a reach. Dissolved nutrient inputs to a reach are estimated as

$$DN_{in} = (DN_i + DN_{up})$$

where $DN_{up}$ is the upstream input of nutrient. Routing to the downstream subcatchment is estimated as

$$D_{out} = D_{in} \exp(-zL_i W_i / Q_{MAF,i})$$

where $z$ is a scaling parameter; and $W_i$ is the width of the stream in subcatchment $i$. The attenuation of dissolved nutrients increases with high nutrient concentrations and for larger stream reaches.

### 2.4 Point sources

Point source inputs of SS and nutrients are also modelled in CatchMODS but are not described here in any detail.

### 2.5 Economics

The costs of management change scenarios are also estimated in CatchMODS. Three types of costs are estimated: fixed, ongoing and landuse-related. Fixed costs are those one-off costs which are incurred during the implementation of riparian and gully zone remediation works. Ongoing costs are the maintenance costs required to maintain the effectiveness of riparian and gully zone remediation works for pollutant control. The landuse-related costs represent the change in gross margins associated with the conversion between landuses. In most instances water quality improvements require conversion from higher to lower value land uses.

## 3. MORUYA AND TUROSS MODEL

The use of the CatchMODS model in the Moruya and Tuross River catchments is presented here as an example of the integration of collateral knowledge in the model development process. The Moruya and Tuross River catchments are located in the Eurobodalla region of the southeast coast of Australia. The catchments are 1420 km$^2$ and 1820 km$^2$ in size, respectively. Both catchments are dominated by native eucalypt forests but grazing and agricultural land uses occur predominantly in the lower parts of the catchments. The catchments are typical of many in the coastal zone of south eastern Australia which face pressure for urban development and land use intensification. Both catchments are sources of drinking water for local communities and support a range of agricultural industries. Their estuaries have high conservation and tourism value.

The application of CatchMODS in the Moruya and Tuross River catchments is an element of a broader program which includes in-stream water quality monitoring, sediment tracing and field measurement. The overarching objectives of the program are to assist local policy makers and managers to (i) identify priority sites (subcatchments) for remediation or management change; (ii) identify appropriate remediation measures; and (iii) estimate the cost effectiveness of remediation and/or management changes. Figure 1 shows the elements of the program and their linkages. The following sections briefly describe these elements and how the knowledge generated has informed the model development process.

### 3.1 Monitoring

An event-based water quality monitoring program was established in the early stages of the research to build understanding of water quality processes and to parameterise and test the model outputs (Figure 1). Three sites are monitored and sediment and nutrient concentration data from several medium sized events have been collected and analysed at two of those sites. Drewry et al. (2008) describes the monitoring program.

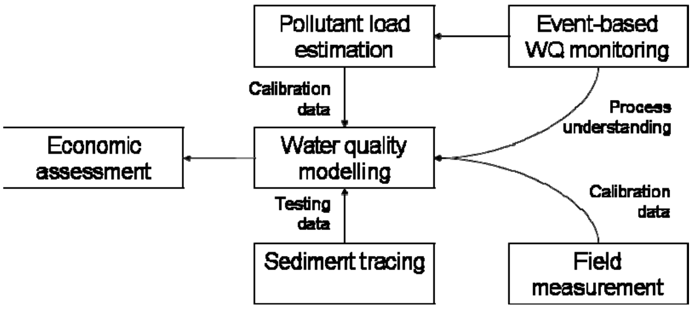

**Figure 1.** Elements and structure of the research program for the Moruya and Tuross River catchments.

Important process knowledge was generated through analysis of the data collected in the monitoring program. For example, it was found in the Tuross River catchment that during flow events the suspended sediment concentration preceded the flow peak by 9-11 hours indicating that: (i) sediment is supply-limited and that catchment-based sediment control measures are likely to prove effective for water quality improvement; and (ii) sediment sources are likely to be from channel sources or areas close to the monitoring site. The nitrate concentration peak was observed to lag behind the flow peak by several hours and it is likely to be related to groundwater inputs of nitrate. The total nitrogen concentration peak lay between the sediment and nitrate peak indicating a particulate and groundwater sources. Antecedent conditions and storm intensity were both observed to influence pollutant loadings with dry antecedent conditions during drought, and high intensity storms resulting in greater pollutant loadings.

There are several implications of these observations on the structure of the model developed for the Moruya and Tuross River catchments. The first is that effort in estimating channel erosion is warranted as channel sources are likely to comprise a high proportion of the total sediment yield. The dominance of nitrate inputs from groundwater necessitates the representation of hydrologic pathways and this is achieved via the use of the IHACRES model with a relatively simple baseflow filtering approach. The effects of antecedent conditions and storm intensity are not explicitly represented in CatchMODS and this is suggested as an area of further research.

A turbidity meter and data logger installed in the lower Tuross River catchment will aid catchment process understanding, improved load estimation and parameterisation of the sediment submodel. The turbidity data is to be used in conjunction with the water quality monitoring data to determine relationships between turbidity and suspended sediment concentration. Such data will also enable more accurate characterisation of events rather than relying on temporally sparser sampling of pollutant concentration and turbidity.

### 3.2 Sediment tracing

Sediment tracing research has been completed in the Moruya and Tuross River catchments to identify those subcatchments contributing disproportionally high suspended sediment loadings. The research was based on the geochemical analysis of deposited and in-stream sediment samples at several stream confluences. The objective was to identify the proportional contribution of sediment from selected tributaries and to provide independent data for testing CatchMODS. A description of the method can be found in Fu et al. (2008).

The Donalds and Burra Creek subcatchment were identified as producing disproportionately high sediment loadings to the Moruya River catchment. The Wadbilliga River subcatchment was similarly identified in the Tuross River catchment. Table 1 presents a comparison of the sediment tracing results of Fu et al. (2008) against preliminary results from CatchMODS. With the exception of the Moruya-Deua River – Burra Creek confluence, the sediment tracing results and model estimates are reasonably well matched. The poor comparison at the Moruya-Deua – Burra Creek confluence is thought to be a result of the difficulty in using sediment tracing techniques to compare between confluences of substantially different sizes. Other factors including possibly erroneous estimates of streambank erosion and the omission of estimates of road erosion require investigation as to their impacts.

**Table 1.** Comparison of the sediment tracing results of Fu et al. (2008) against preliminary results from CatchMODS.

| Confluence name (A-B) | A% by sediment tracing | Mean error (%) | CatchMODS estimate |
|---|---|---|---|
| Burra– Donalds Creeks | 30.09 | 7.36 | 30 |
| Moruya-Deua River – Burra Creek | 45.18 | 11.33 | 95 |
| Tuross – Wadbilliga Rivers | 54.30 | 28.37 | 61 |
| Tuross River – Belimbla Creek | 83.95 | 3.25 | 70 |

Further research is required into identifying the relative contributions from the different sediment sources in the catchment. This is to be attempted in a Goodenough Gully subcatchment of the Moruya River catchment where the proportional contribution of road erosion to the total sediment load is to be estimated using geochemical tracing techniques. Opportunities also exist to distinguish between surface and subsurface sediment sources using radionuclide tracing techniques.

### 3.3 Field measurement and observation

All of the parameters of CatchMODS are theoretically measurable. In practice they are obtained via field measurement within a study catchment or extrapolated from other catchments. In the application of CatchMODS in the Moruya and Tuross River catchments, several catchment-specific data sets were obtained. For example, the location and severity of gullies were field-checked against mapping acquired through air photo interpretation. The accuracy of the mapping was assessed to be of high quality with few errors of omission or misclassification. The dimensions of the gullies (width and depth) were also measured to parameterise the sediment submodel. The gully width divided by the estimated age of the gully provides an upper limit on the lateral erosion rate which is otherwise extrapolated from catchments in the same region.

A range of soil physical and chemical data is required as input to the modelling. This included estimates of sediment bulk densities, suspended sediment proportions and nutrient concentrations for gully and streambank erosion sites. Analyses of soils under different land uses have also been measured. A preliminary description of this work and its incorporation in CatchMODS is provided in Fu et al. (2005). Nutrient concentrations of groundwater were also analysed from accessible bore sites across the catchment.

The data so far collected for the application of CatchMODS in the Moruya and Tuross River catchments is data readily obtainable. Longer term information is required, for example, to improve confidence in measurements of the rates of gully and streambank erosion.

## 4. SUMMARY

This paper has described progress on the modelling of sediments and nutrients to inform management effort. A full description of the structure of the catchment-scale model known as CatchMODS has been presented. This has included a description of each of its hydrologic, sediment, nutrient and economic submodels. A discussion of the integration of knowledge from a range of collateral sources to inform the development of the model was also made. Useful progress has been made towards improving the model though the integration of this data. Challenges remain to further incorporate collateral knowledge into the model development and application process. Such challenges present need to be actively perused to improve confidence in model outputs.

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