18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

An evaluation of several approaches to estimate impacts of landuse change on nutrient and hydrologic balances

Beverly, C.[1], **O. Vigiak**[1], **B. Christy**[1], **M. Hocking**[2], **J. Whitford**[1], **A. Roberts**[1],

[1] *Department of Primary Industries, Rutherglen Centre, Rutherglen, Victoria*
[2] *Hockingetal. Pty Ltd, Hampton, Victoria*
Email: craig.beverly@dpi.vic.gov.au

Abstract: This paper presents three modelling approaches commonly used to estimate the nutrient balance within large catchments and outlines the rationale of the different model constructs. Each model is evaluated by application to a catchment in north central Victoria, Australia, that has an area of 371,000 ha and comprises mixed landuse enterprises. The catchment is also in connection with a groundwater system that contributes on average 20% of streamflow. Model results are shown to compare favourably with available nitrate observation data. However results indicate that the lumped and extrapolated approaches, whilst easily calibrated to stream flow data, do not adequately describe the within-catchment processes. The physics-based model is the only approach capable of representing spatially explicit surface water, leached water and groundwater concentrations across the catchment. This modelling approach identified the importance of transport of nitrate within overland flow events and groundwater discharge to stream, a hitherto undocumented process within the study catchment. The objectives of this paper are to (i) contrast the development rationale and basic assumptions currently embedded into existing modelling approaches to estimate catchment nutrient balances, (ii) evaluate and compare the capacity of the different models to account for land management changes by application to a focus catchment and (iii) present the strengths and weaknesses of each of the modelling approaches. Presented results suggest that the physics-based catchment modelling approach has superior predictive capability to account for the impacts of land management change than the process-based and generation rate-based approaches. However until the landscape attenuation and transformation processes are generalised with confidence for inclusion into the more physics-based catchment models it is recommended that the generation rate-based approach linked to a catchment model capable of predicting hydrologic pathways at the land management scale be adopted. This paper concluded that all of the modelling approaches evaluated require further development.

Keywords: *Nutrient modelling, catchment modelling, watershed models, stream attenuation.*

1. INTRODUCTION

A wide variety of catchment scale hydrologic and water quality models have been used to predict contaminant source and transport across catchments and in surface waters. These models can be characterised on the basis of their process complexity and the temporal and spatial scales adopted in these models (Singh 1995). Newham and Drewry (2006) categorise catchment-scale models in use for modelling nutrient generation in Australian catchments into four main approaches: (1) generation-rates based, (2) process-based, (3) physics-based and (4) index-based. Generation-rates based include the "statistical" and empirical approaches based on deriving responses from observations. Such models are often parameterised to specific catchments and take no account of the spatial patterns within the catchment to which they are applied. In contrast, process-based models usually include transfer functions and are based on knowledge of nutrient generation processes. The process-based models are regarded as being well suited to lumped catchment studies and are typically calibrated against observed data including stream discharge and nutrient concentration data. Alternatively physics-based or "deterministic" models are derived from detailed plot scale studies and typically describe fine scale complex interactions. Index-based models are not considered in this study. Assigned to this continuum are contemporary models widely adopted internationally and in Australia.

The objectives of this paper are to:

(i) contrast the development rationale and basic assumptions currently embedded into existing modelling approaches to estimate catchment nutrient balances,

(ii) evaluate and compare the capacity of the different models to account for land management changes by application to a focus catchment, and

(iii) present the strengths and weaknesses of each of the modelling approaches.

2. MODELLING METHODOLOGY

The level of complexity or process detail represented by model descriptions of hydrology and nutrient processes varies with the extent to which "statistical/empirical" and "deterministic" methods are used (Alexander *et al*. 2002, Schwarz *et al.*, 2006). To evaluate the capacity of different model structures and process specification to describe the impact of land management changes on contaminant sources and transport in catchments and surface waters three modelling approaches were considered, namely (1) HowLeaky? linked to CatchMODS, (2) Generation Rate Assignment (CAT-Gen) approach and (3) Catchment Analysis Tool (CAT). These models in broad terms represent generation-rates based (CAT-Gen), process-based (CatchMODS) and physics-based (CAT) types with regards to the approach used to estimate nutrient dynamics. The underlying assumptions and model constructs of each approach are summarised below and in Table 1.

2.1. HowLeaky? linked to CatchMODS

In this approach soil/water/plant interactions at point scale were modelled using HowLeaky? (Rattray *et al.*, 2004) which is based on the crop productivity and erosion model PERFECT (Littleboy *et al.*, 1996). Differences between the models are detailed in Robinson *et al*. (2007). This one-dimensional model simulates crop growth, components of the water balance and soil loss on a daily timestep. The P model developed for HowLeaky? calculates total P on a daily basis and is assumed to be the sum of dissolved and particulate forms. Particulate P includes P sorbed by filterable soil particles and organic matter while dissolved P is immediately available for biological uptake. The loss of particulate P is based on erosion generated sediment concentrations in runoff, total P in the soil and a delivery ratio. The delivery ratio is the ratio of sediment delivered to a waterway to the total amount of sediment eroded from a hillslope or paddock.

The Catchment-Scale Modelling of Diffuse Sources (CatchMODS) model framework integrates hydrologic, sediment and nutrient export models in a GIS user interface (Newham *et al.*, 2004). The model includes processes used in the SedNet model (Prosser *et al.*, 2001) including gully, hillslope and stream bank erosion. TP export is estimated directly from observed suspended sediment load. In this application, daily runoff, deep drainage, soil loss and TP estimates derived using HowLeaky? for various landuse by soil by climate combinations were used as inputs into CatchMODS. CatchMODS is an example of a predominantly process-based model.

2.2. Generation Rate Assignment

The Generation Rate Assignment approach is based on solving the hydrological pathways within a catchment and assigning nutrient concentrations to each landuse using an optimisation approach aimed at matching end-of-valley measured water quality data (Barlow *et al*., 2009 *this conference*). The nutrient concentration assigned to each landuse is constrained within the predefined limits reported in the Catchment Management Support System (CMSS) which summarises the long term nutrient loads delivered to stream derived from national field experiments (Davis and Farley 1997; Marston *et al*., 1995).

In this approach the CAT model (refer below) was used to estimate catchment hydrologic processes including surface runoff, lateral flow, evapotranspiration and recharge on a daily timestep for each landuse with allowance for spatial catchment location and attributes. Model predictions were combined to a monthly time-step for integration into the lumped single-layer 2CSalt groundwater model (Gilfedder *et al*. 2007) The 2CSalt model is calibrated to predict monthly baseflow and streamflow components. Nutrient generation was described for each landuse using an effective mean concentration (EMC) and dry weather concentration (DWC) for the monthly quickflow and baseflow estimates predicted by 2CSalt. Nutrient loads are calculated and summed for each landuse to derive nutrient loads for each sub-catchment.

Hereafter this model is referred to as CAT-Gen as it combines a physics-based deterministic approach to describe the hydrologic response of a catchment using CAT (refer below) and a generation rates-based quasi-statistical approach to describe contaminant processes.

2.3. Catchment Analysis Tool

The Catchment Analysis Tool (CAT) was the most complex model used for the study. It comprises a suite of farming system models that account for topography, soil type, climate and time-varying landuse linked into a catchment framework with allowance for landscape connectivity and connection to a distributed, multi-layered groundwater model (Beverly *et al*., 2005; Weeks *et al*., 2008). In this application the catchment framework was linked to the fully distributed multi-layer groundwater model MODFLOW (McDonald and Harbaugh, 1988). The framework estimates the impact of various forms of intervention using a combination of paddock/farm scale models and a lateral flow model that are integrated into a regional catchment scale framework (Hocking and Beverly, 2009 *this conference*). Connection to adjacent up-slope and down-slope topographic elements enables the lateral redistribution of surface runoff and interflow (e.g. perched watertables) and facilitates the transport of water and nutrients from the top of the catchment to streams and end-of-valleys.

The nitrogen and phosphorus modules are based on the algorithms incorporated in the SWAT model (Neitsch *et al*. 2001). The components of the nitrogen cycle considered include mineralisation, nitrification, volatilisation and denitrification of soil layers, and the corresponding allocation between pools of nitrogen concentrations. The model monitors five different pools of nitrogen within the soil, featuring two inorganic mineral pools and three organic pools. Organic nitrogen is then further partitioned into fresh organic nitrogen associated with crop residue, and humic organic nitrogen associated with active and stable pools. The phosphorus module simulates six different pools of phosphorus. Three pools describe the inorganic forms of phosphorus (representing soluble, active and stable pools) and the remaining three pools represent the organic forms of phosphorus associated with crop residue, and an active and stable humus pool. The phosphorus module considers mineralisation, decomposition, sorption and the transfer of phosphorus between pools.

Table 1: Comparison of model features

Model feature	**HowLeaky?/CatchMODS**	**CAT-Gen**	**CAT-NaP**
Hydrological assessment	Process-based	Physics-based	Physics-based
Contaminant processes	Process-based	Generation rates-based	Physics-based
Nutrient considered in study	P	N and P	N and P
Time step	Steady state	Monthly	Daily
Groundwater process	No	Lumped	Distributed
Sediment	Hillslope, gully, stream bank	Hillslope	Hillslope

This modelling approach adopts a physics-based deterministic approach to describe both the hydrologic response of a catchment and contaminant generation and transport processes. Hereafter this model is referred to as CAT-NaP.

2.4. Summary of modelling approaches

Key features of the three modelling approaches considered in this study are summarised in Table 1. It must be noted that whereas CatchMODS includes modules to estimate N and P processes, in this application, due to the absence of a nitrogen module in HowLeaky?, the linked HowLeaky?CatchMODS approach was only used to predict catchment scale P dynamics; whereas the CAT-Gen and CAT-NaP models were used to predict both N and P catchment scale processes.

3. MODEL APPLICATION

The model comparison study catchment was the Avon-Richardson (Figure 1) located in the North-Central Catchment Management Authority region of Victoria, Australia, and covers an area of 371,000 ha.

3.1. Data sets

Available spatial data layers were used. Landuse and soil layers were based on 1:100,000 mapping, whereas slope, aspect and climate surfaces (specifically mean annual rainfall, temperature, solar radiation and potential evapotranspiration) were derived using 1:25000 scale digital elevation data. The climate surfaces were used to extrapolate and construct daily climate data files at each grid point from recorded meteorological data sets. The current landuse spatial layer suggests landuse comprises 52% cropping, 37% grazing, 6% trees and the remaining 5% constituting urban infrastructure and water bodies. Mean annual rainfall ranges from 350 to 765 mm/year.

3.2. Landuse and fertiliser application rates

Average decadal historical fertiliser application rates were estimated by local farmers as part of a DPI research program on linking paddock scale actions to water quality outcomes, in collaboration with the North-Central Catchment Management Authority (CMA). The catchment was broadly grouped into five zones, specifically the north and central cropping zones, the zones of mixed cropping and pasture enterprises and the southern grazing zone (Vigiak *et al.* 2009 *this conference*). Landuse within the cropping zones changed from a predominately wheat-pasture-fallow system in the 1950's to a canola-wheat-barley-pasture/legume system in the 1990's to current. Within the mixed cropping zones the landuse is predominately a wheat-fallow-pasture system with varying durations of pasture whereas the grazing zone maintains native pasture on steep slopes and an annual pasture system on the lower slopes. With respect to fertiliser applications both the HowLeaky? and CAT-NaP applied P and N application rates by zones by decades. Opportunity applications were assumed to be triggered on soil moisture contents within the root zone being above 75% saturation within a one week period commencing 15 August.

3.3. Representation of groundwater dynamics

The CatchMODS model does not model groundwater dynamics whereas the CAT-NaP modelling approach estimated groundwater contribution to stream based on results derived using a calibrated three layer MODFLOW

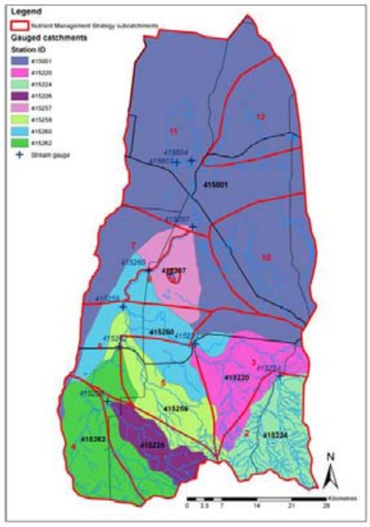

Figure 1. Sub-catchment and stream gauge locations. Also shown are the nutrient management zones used by the Catchment Management Authority to prioritise and report nutrient management strategies.

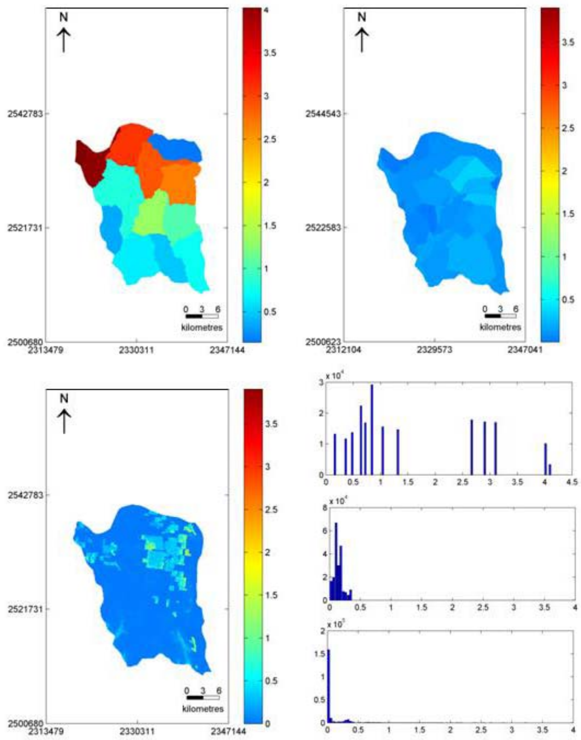

Figure 2. Estimated P generated (kg/ha) using CatchMODS (top left), CAT-Gen (top right) and CAT-NaP (bottom left). Corresponding distributions are in the same order from top to bottom**.**

groundwater model which adopted a uniform grid of 100 m resolution and weekly time-steps. In contrast the CAT-Gen approach estimated groundwater contribution to stream based on modelling lumped groundwater units with limited lateral connectivity.

3.4. Stream attenuation

Both CatchMODS and CAT-NaP models apply a stream attenuation coefficient to each stream reach. In contrast the CAT-Gen model does not explicitly account for attenuation processes.

4. RESULTS

The streamflow derived using CatchMODS was based on fitting the combined daily runoff and deep drainage estimates derived using HowLeaky? with a regression equation to measured streamflow. The regression analysis defined streamflow to be 21% of water excess (the sum of runoff and deep drainage); this approach assumed baseflow was equivalent to deep drainage. In contrast the other two approaches are underpinned by the same hydrological model which separates measured streamflow into quickflow and baseflow components. The monthly measured versus predicted streamflow coefficient of efficiency derived using each approach for gauge 415220 (Figure 1) was calculated to be 0.76, 0.68 and 0.69 for CatchMODS, CAT-Gen and CAT-NaP respectively. The difference between CAT-Gen and CAT-NaP monthly streamflow was due to different groundwater baseflow estimates.

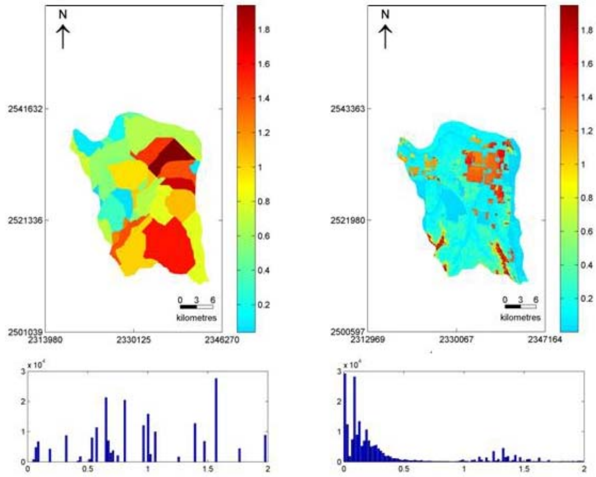

Figure 3. Estimated N generated (kg/ha) using CAT-Gen and CAT-NaP models. Corresponding distributions are also shown.

The P and N loads generated from the upper catchment are shown in Figures 3 and 4 respectively. Note that CatchMODS derives a single lumped mean annual estimate whereas the CAT-Gen and CAT-NaP models produce monthly and daily estimates respectively from which spatial distributions can be calculated. Only the mean annual average results are shown in Figures 3 and 4. The associated distributions are also shown in these figures. The comparison between measured and predicted water quality at a representative gauge is summarised in Table 2. The selected gauge was 415220 and has a contributing area of 52,095 ha.

Table 2 summarises the mean annual P and N (in brackets) results derived for gauge 415220 for the period 1980-2000. All model results were compared with the current nutrient management plan used by the CMA (NCCMA, 2003). The 12 nutrient zones are shown in Figure 1. In the case of CAT-NaP the nutrient contribution from gully and stream bank erosion was sourced from the nutrient management plan as these processes are not modelled explicitly within the CAT-NaP framework.

Table 2: Observed versus simulated P and (N) estimates for gauge 415220 for the period 1980-2000.

	measured	CatchMODS	CAT-Gen	CAT-NaP
Mean annual streamflow (ML/annum)	20,144	21,128	15,189	19,383
Mean annual quickflow (ML/annum)	15,902	n/a	10,233	16,869
Mean annual baseflow (ML/annum)	4,242	0	4,956	2,514
Simulated Nutrient balance				
P and (N) load from groundwater (tonnes/annum)		0	0.24 (9.36)	0.20 (10.70)
P and (N) load from gully erosion (tonnes/annum)		0.58 (n/a)	n/a	0.61[2] (8.99[2])
P and (N) from catchment landuse (tonnes/annum)		2.19 (n/a)	4.39 (43.46)	3.87 (33.78)
Total estimated catchment P and (N) (tonnes/annum)	**4.73[1] (56.17[1])**	**2.77 (n/a)**	**4.63 (52.82)**	**4.69 (53.47)**
Catchment P and (N) maximum (tonnes/month)	3.74 (45.20)	n/a	6.36 (65.37)	11.7 (63.77)
Catchment P and (N) mean (tonnes/month)	0.40 (4.87)	n/a	0.37 (4.40)	0.45 (1.79)
Catchment P and (N) median (tonnes/month)	0.007 (0.14)	n/a	0.03 (0.53)	0.001 (0.013)
Catchment P and (N) standard deviation (tonnes/month)	0.98 (11.27)	n/a	0.89 (9.76)	1.61 (6.14)

1 based on flow stratified sampling analysis

2 estimated as 13% for P and 16% for N (NCCMA, 2003)

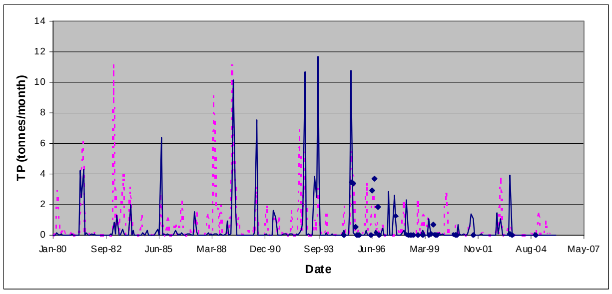

Figure 4. Observed (dots) versus predicted TP derived using the CAT-Gen (dashed line) and CAT-NaP (full line).

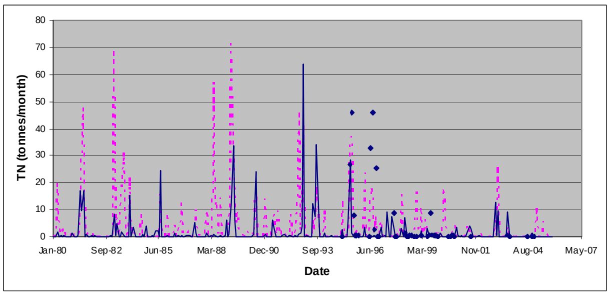

Figure 5. Observed (dots) versus predicted TN derived using the CAT-Gen (dashed line) and CAT-NaP (full line).

Figures 5 and 6 show the monthly measured and predicted P and N load for gauge 415220 derived using the CAT-Gen and CAT-NaP modelling approaches.

5. DISCUSSION

The linked HowLeaky? CatchMODS has limited temporal representation of nutrient generation processes as it only reports mean annual estimates. Predicted streamflow is however calibrated to measured daily flows so as to enable estimation of stream bank erosion quantities which are subsequently collapsed to a mean annual value. In this application the daily estimates of runoff and deep drainage derived using HowLeaky? were inputs into CatchMODS and used to estimate daily streamflow (and ultimately mean annual stream bank erosion) whilst daily soil loss and TP were averaged to a mean annual value. Whilst not explicitly accounting for landscape connectivity, the capability of incorporating finer scale model outputs (eg from HowLeaky?) into the CatchMODS GIS framework provides enhanced model functionality. Results derived from this linked model approach suggest that gully erosion is the dominant mechanism for the delivery of phosphorus to stream. This is in contrast with CAT-NaP which reports that groundwater processes contribute equivalent loads. Whilst the CatchMODS framework does not explicitly simulate complex groundwater processes and CAT-NaP does not account for gully and stream bank erosion it is noteworthy that the estimates derived from each of these processes are predicted to be of the same magnitude. This suggests that predictions from each of these models may compensate for processes not explicitly simulated within their respective frameworks and suggests further development of both these models is required. However the current linked CatchMODS approach is considered suitable for catchment prioritisation studies.

The CAT-Gen approach is shown to match monthly stream flow to a reasonable degree of accuracy. Results suggest that the within-catchment hydrologic processes and spatial representation of water balance components are well represented. However this approach does not take account of the nutrient application history of land management units. Rather it adopts a generation rate approach by which parameter values are obtained by calibration which lump both generation rate, transport and transformation processes into values specific to that catchment and which cannot be separated. As such, and given that the model is calibrated to historical flow data, this approach may have limited predictive capability to describe the impact of landuse/land management change or future climate scenarios.

In the case of the CAT-NaP approach the fraction of N and P load entering the streams which is delivered to catchment outlet (0.95 for N and 0.86 for P) was found to be consistent with Elliot *et al*. (2005). The low stream attenuation losses are due to the catchment low flow regime (<0.02 m^3/sec/km) and catchment topography. Inter-model results suggest that the CAT-NaP model requires enhancement to account for gully and stream bank erosion processes in the context of representing sediment associated nutrient transport processes. Additionally the model requires more robust derivation of within-stream attenuation to account for sedimentation and transformations between receiving stream reach and catchment outlet stream gauge.

The different spatial patterns of N and P derived from each model are a function of model construct. CatchMODS adopts a lumped spatial representation, whereas the CAT-Gen and CAT-NaP models operate at the resolution of the landuse layer. CAT-Gen assigns nutrient concentrations to each landuse whereas CAT-NaP estimates nutrient generation at each landscape position accounting for soil, topography, aspect etc. In all cases, the spatial patterning of nutrient generation was found to be in accord with published point scale data. However in the absence of more detailed data it is reasonable to assume that models describing landscape specific hydrologic pathways may provide a better spatial representation of N and P generation.

6. CONCLUSIONS

Results presented in this paper demonstrate the predictive capability of different catchment scale nutrient modelling approaches. Adequate description of within-catchment flow pathways and water excess is fundamental to describing nutrient transport processes. In all cases considered this was achieved using plot scale farming system models. The HowLeaky?CatchMODS linked modelling approach is identified as being suitable for catchment prioritisation studies. For investigations requiring temporal responses and/or finer spatial predictions the CAT-Gen and CAT-NaP approaches are considered more appropriate. However, the nutrient generation rate approach adopted by the CAT-Gen model does not explicitly account for nutrient sources/sinks at each landscape management unit which limits the potential to assess the impact of land management scenarios. In contrast, the CAT-NaP model adopts a physics-based approach capable of describing the nutrient generation process in detail at each landscape management unit. However this approach requires further development to better represent the attenuation and transformation processes across landscape and within-stream. Whereas this approach has superior predictive capability to account for the impacts of land management change than the process-based and generation rate-based approaches, it is concluded that the CAT-Gen approach be adopted until the landscape attenuation and transformation processes are generalised with confidence for inclusion into the more physics-based catchment models.

ACKNOWLEDGMENTS

The authors acknowledge the contribution of Lindsay Ezard for the provision of local information.

REFERENCES

Alexander, R.B., Smith, R.A. and Schwarz, G.E. (2000). Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico, Nature, 403, p758-761.

Beverly, C., M. Bari, B. Christy, M. Hocking and K. Smettem, (2005), Predicted salinity impacts from land use change: a comparison between rapid assessment approaches and a detailed modelling framework. Australian Journal of Experimental Agriculture, 45, 1453-1469.

Davis, J.R. and Farley, TFN (1997) CMSS: policy analysis software for catchment managers, Environmental Modelling and Software, 12, 197-210.

Elliot, A.H., Alexander, R.B., Schwarz, G.E., Shankar, U., Sukias, J.P.S. and McBride, G.B. (2005). Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW, J. Hydrology (NZ), 44(1), pp1-27.

Gilfedder., M. Littleboy, M. and Stenson., M. (2007). Two modelling approaches for predicting water and salt generation to upland stream: BC2C and 2CSalt, MODSIM07, p 1478-1484.

Littleboy, M., Cogle, A.L., Smith, G.D., Yule, C.D.F., Rao, K.P.C. (1996) Soil management and production of Alfisols in the semi-arid tropics, I. Modelling the effects of soil management and runoff and erosion. AJSR, 34, 91-102.

McDonald M C, Harbaugh A W (1988) 'MODFLOW, A modular three-dimensional finite difference ground-water flow model.' pp.1-586. Chapter A1 Open-file report 83-875, (US Geological Survey, Washington DC).

Marston, F., Young, W. and Davis, R. (1995). Nutrient generation rates data book, 2nd edition, CSIRO Division of Water Resources, LWRRDC and SWB, Canberra.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2001) 'Soil water assessment tool theoretical documentation, Version 2000.' Grassland, Soil and Water Research Laboratory, Temple, Texas.

Newham, L.T.H. and J.J. Drewry (2006), Modelling catchment-scale nutrient generation, CSIRO Land and Water Technical Report 28/05, pp 39.

Newham, LTH, 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 and Software, 19, 1029-1038.

North Central Catchment Management Authority,(2003). Avon-Richardson Nutrient Management Strategy, January 2003, ISBN 0 9750 4562 8, pp99.

Rattray, D.J., Freebairn, D.M., McClymont, D., Silburn, D.M., Owens, J. and Robinson J.B. (2004) Howleaky? – the journey to demystifying simple technology. Conserving soil and water for society: Sharing Solutions ISCO 2004, the 13th International Soil Conservation Organisation Conference, Brisbane, July, 2004.

Robinson, B., D. Rattray, D. Freebairn, D.M. Silburn and D. McClymont (2007) Using a simply hydrologic model to link management to nutrient concentration and loads in runoff, MODSIM07, p 2116-2123.

Singh, V.P. (1995). Computer models of watershed hydrology: Highland Ranch, CO, Water Resources Publication, 1, 144p.

Schwarz, G.E., A.B. Hoos, R.B. Alenander and R.A. Smith (2006) The SPARROW Surface Water-Quality Model: Theory, Application and User Documentation, U.S. Geological Survey Techniques and Methods, 6-B3, 248 p.

Weeks, A., Christy, B., Lowell, K., and Beverly, C. (2008). Catchment Analysis Tool (CAT) – Demonstrating the benefits of interconnected biophysical models. in: Landscape Analysis and Visualisation. Spatial Models for Natural Resource Management and Planning. (eds. Pettit, C., Cartwright, W., Bishop, I., Lowell, K., Pullar, D., Duncan, D.) Springer- Verlag Publishers