Modelling Nutrient Transport in Currency Creek, NSW with AnnAGNPS and PEST

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Abstract: The modelling package Annualized Agricultural Nonpoint Source model, AnnAGNPS, was applied to the prediction of export of nitrogen and phosphorus from Currency Creek, a small experimental catchment within the Hawkesbury-Nepean drainage basin of the Sydney Region. The catchment is 255 hectares in area and has experienced extensive soil erosion and losses of nutrients from intensive vegetable cultivation, irrigated dairy pasture and poultry farms. Simulations of nitrogen and phosphorus loads in the Currency Creek catchment were performed at various temporal scales and the degree of calibration was quantified by comparing the simulated data with the monitoring results. In addition, the model independent, nonlinear parameter estimation code PEST, was applied for sensitivity testing to determine and assess the relative importance of the key parameters of the model. Event flows were simulated satisfactorily with AnnAGNPS but only moderate accuracy was achieved for prediction of event-based nitrogen and phosphorus exports. The biggest deviations from the measured data were observed for daily simulations but trends in the generated nutrients matched observed data. Despite achieving good resemblance between measured and predicted phosphorus loads the model showed high level of sensitivity to assigned pH values for topsoil. Increase in pH by one unit resulted in up to 34% increase in model generated particulate phosphorus load.

Keywords: AnnAGNPS; PEST; Nutrient transport; Catchment modelling

1. INTRODUCTION

Assessing contributions of nitrogen and phosphorus from diffuse agricultural sources presents a constant challenge to researchers and water quality managers. The major difficulty with quantifying nutrient loads in runoff can be attributed to the fact that runoff events are highly unpredictable and that a simple aggregation of single sources distributed across the catchment does not reflect a tributary load entering a waterway. Rapidly changing land use patterns and management practices contribute even further to the complexity of the problem. In addition, in low-yielding catchments with ephemeral streams, the relationship between rainfall and runoff might be very nonlinear as antecedent physical soil attributes and conditions are critical to catchment response to rainfall.

It is then inevitable that catchment models are increasingly used as tools for assessment of pollutant loads and simulation of catchment processes and management practices in an effort to address diffuse source pollution. A large array of models exists, varying in complexity, input data requirements, predictive capabilities and suitability for Australian conditions. Also, the degree to which different models attempt to simulate catchment conditions and the subsequent physical processes which control generation and transport of pollutants, vary considerably.

In this paper, applicability and predictive capacity of the Annualized Agricultural Non-Point Source model (AnnAGNPS) in Australian conditions is examined. It is a preliminary step to determine minimum site-specific data requirements to predict contribution of diffuse sources to water contamination. A combination of field data and modelling is used to estimate on-site erosion and water quality effects and, in particular, nitrogen and phosphorous transport through the experimental catchment of Currency Creek.

2. IMPLEMENTATION OF AnnAGNPS MODEL

New improved AnnAGNPS continuous simulation model versions 1 and 2 were used as the first attempt in Australia to test the model capabilities of simulating nutrient transport. Until 1999, the AGNPS model [Young et al., 1989] was capable only of simulating a single storm event and required a predefined square-grid discretisation of the modelled area to represent spatial variability of catchment attributes.

2.1 Model Description

The AnnAGNPS 2001[1] modelling system was developed by the US Department of Agriculture (2001) to evaluate diffuse source pollution and to assist with management of runoff, erosion and nutrient movement in rural ungauged catchments. The pollutant loading surface runoff module simulates non-point source pollutant generation and performs risk and cost/benefit analysis. It can simulate chemical transport of particulate and soluble forms of phosphorus and nitrogen, organic carbon and pesticides using routines derived from the CREAMS model [Knisel, 1980].

Although AnnAGNPS uses major hydrologic concepts of the AGNPS model, it improves and expands modelling of physical processes governing routing of sediment and pollutants associated with runoff events. In particular, the continuous simulation model allows better representation of the processes involved in transport and deposition of the generated sheet and rill erosion. As part of the delivery process, the overland deposition of the eroded sediment rather than a complete delivery of the material to the stream system, is simulated. New components, such as Crop Data, Feedlot Management Data, Strip Data and Contour Data, have been also added to the model allowing for better characterisation of the modelled catchment. The major departure from the original AGNPS concept lays in: 1) different approach to catchment discretisation and topographic representation of the modelled area; 2) introduction of time variant parameters; 3) integration of GIS software tools into the modelling system to analyse terrain-dependent parameters and hydrologic characteristics of the drainage system.

The AnnAGNPS model combines the latest advances in GIS data manipulation and physical characterisation of the catchment, offering modelling opportunities for ungauged areas or for areas with limited data prohibiting the use of models relying on calibration for derivation of input variables. Nevertheless, the input data set for AnnAGNPS is extensive and may consist of up to 33 sections of data including catchment physical characteristics (e.g. soil type, texture, particle distribution, pH, hydraulic conductivity, organic and inorganic N and P ratios in soil layers, land slope, slope length, steepness), detailed management practices and daily climatic records of minimum and maximum temperatures, rainfall, dew point, sky cover and wind speed.

Originally, the model for the Currency Creek subcatchment was developed in AnnAGNPS ver.1, which was then converted and re-run when AnnAGNPS ver.2 was released early 2001. Version 2 offers improvements in the runoff and sediment yield simulation by using automatically generated input parameters. It also corrects evident problems with phosphorus generation procedures found in version 1.

2.2 Study Area–Currency Creek Catchment

Data collected during an intensive 3 year monitoring study conducted in a 255-hectare catchment of Currency Creek was used to test capabilities of the AnnAGNPS model. The catchment is situated on the southern slopes of a valley, 4 kilometres north of Richmond and approximately 90 kilometres north-west of Sydney CBD, NSW.

The monitored catchment comprises heterogenous, rapidly changing farming and residential land uses. The upstream part of the catchment consists of intensive irrigated grazing, a dairy farm and an unimproved pasture (66 ha), while semi-improved cattle grazing, hobby farms, small areas of horse agistment and a turf farm are located throughout the lower regions of the catchment. There are market gardens (20 ha) in the central part of the catchment and a single poultry farm adjoins the market gardens on the south bank of the creek.

The catchment was instrumented with 5 fully automated monitoring stations recording rainfall and flow data and collecting water samples. At each monitoring station the data was logged at fixed 3-hourly intervals, even between storm events when there was no water flow in the monitored stream. During storm events an occurrence of rainfall and/or a predetermined change in discharge triggered the logger to record data at intervals of 1 to 5 minutes depending on the size of the drainage area and the flow control structure used. The event-based water quality monitoring was conducted from May 1995 to March 1997 and during that time up to 13 events were sampled at each station. Water samples were analysed for suspended solids, soluble and particulate forms of nitrogen and phosphorus, as well as for total nitrogen and phosphorus. The period-weighted method was used to compute the event nutrient loads [Dann et al., 1986]. Table 1 shows the hydrologic characteristics of the

[1] http://www.sedlab.olemiss.edu/AGNPS.html

observed major events and corresponding measured loads of soluble and particular nitrogen and phosphorus measured at the outlet of the catchment.

Table 1. Characteristics of the calibration events monitored at the outlet of Currency Creek.

Event Duration	Rainfall (mm)	Discharge (m^3)	Peak Discharge (m^3/s)	Soluble N (kg)	Sediment N (kg)	Soluble P (kg)	Sediment P (kg)
24-25 / 09 / 1995	95.0	70225	2.82	554.3	36.6	29.3	10.0
30-31 / 08 / 1996	85.8	74572	1.69	598.7	84.6	86.7	37.1
29 / 09 / 1996	54.1	8773	0.29	30.2	16.2	6.9	5.1
29-31 / 01 / 1997	115.8	54246	0.75	477.4	74.7	63.0	43.6
11-12 / 02 / 1997	164.6	214026	5.15	798.5	162.3	257.8	101.7

2.3 Catchment Schematisation and Input Parameters

Topographic parameterisation software provided with the AnnAGNPS modelling system was used for digital landscape analysis of the raster elevation model (DEM). As a result of DEM data processing the study area was discretised into 13 drainage areas (amorphous cells) and 6 reaches. Terrain-based geomorphic and drainage parameters were also determined. In the Currency Creek model, approximately 770 data fields had to be assigned ranging from simple vegetation codes or links between the model cells and data sections to detailed topographic, hydrologic, geomorphic and agronomical parameters.

The AnnAGNPS Input Editor was used to develop and modify the input data to the pollutant loading model. Most of the input parameters were sourced from the measured data and where the data was not available, the parameters were estimated based on the literature and the reference data provided with the modelling system.

Rainfall dependant parameters, which reflect the ability of a storm to cause erosion, are expressed by average annual rainfall erosivity (R) and rainfall energy-intensity factor (EI30) for a 10-year average recurrence interval (ARI) (Table 2). Spatial and temporal distribution of rainfall erosive power differs throughout Australia and during the year. In general, R increases during summer months when high intensity storms are most common [Rosewell, 1993]. The average value of R for the Richmond area was interpolated from a map showing the distribution of the R factor. A cumulative value of R index based on a 15-day period was also entered as part of the input data. The maximum rainfall intensity (I) for an event with a recurrence period of 10 years was determined from the IFD data for Richmond supplied by the Bureau of Meteorology, and the storm energy was estimated from the formula developed for eastern Australia by Rosewell, [1993].

Table 2. Selected RUSLE parameters.

Parameter	Value
Rainfall Erosivity (R) [MJmm/ha-hr-annum]	2500
Energy Intensity (EI) (10-year ARI) [MJmm/ha-hr]	1888
30-min rainfall intensity (10-year ARI) [mm/hr]	65.21

Designed rainfall distribution provides means for estimation of peak discharges and generation of sediment [USDA, 1986]. The Type-II synthetic rainfall distribution was selected for the Currency Creek catchment. The selection was based on experimental studies [Browne, 1999] showing that it was the most representative hyetograph for areas where short-duration summer thunderstorms dominate.

Runoff volumes are predicted using the Soil Conservation Service curve number method (CN). For the purpose of this study the initial curve numbers were selected using field measurements of rainfall and runoff. A method of CN curve fitting by graphical plotting of daily rainfall and runoff volumes was used [Boughton, 1989]. After constructing of the plot of P against Q, a visual comparison of plotted data with the USDA curve number plots was conducted to select the appropriate median curve number for the

Currency Creek catchment. Three distinct groups of storm runoff CN were noticed, namely 50 – 55, 75 – 80 and 90 – 95 showing a very high runoff potential.

3. EVALUATION OF MODEL PERFORMANCE

The AnnAGNPS outputs were simulated for the outlet of the Currency Creek. Model optimisation was performed on five well-defined runoff events varying in duration, event magnitude and catchment conditions (Table 1).

Performance and simulation accuracy of Ann AGNPS was assessed based on the ability of the model to predict runoff and nutrient loads, and by identifying the relative importance of the key parameters. The evaluation was carried out in two stages. At first calibration focussed on the hydrologic features of runoff, such as peak discharge and event flow volume, as they have profound effect on water quality and, in particular, generation and transport of sediment-associated pollutants. It was observed that a single CN value had a major effect on computed event flows and the following calibration focused on systematic adjustment of CN values within AnnAGNPS model.

Nutrient loads, however, displayed more complex and often contradictory responses to changing input variables. It was then decided to use model independent nonlinear parameter estimation software PEST to help optimise input parameters and identify the ones having major effect on the model outcomes. PEST uses Gauss-Marquardt-Levenberg algorithm, which combines the advantages of the inverse Hessian method and the steep descent method [Press et al., 1989]. By varying user defined model inputs, it attempts to minimise the weighted sum of squared differences between the model generated values and those measured in the field. The goodness of fit is apparent from the value of optimised objective function and is also provided by computed correlation coefficient independent from the number of observations and levels of uncertainty associated with those observations allowing therefore for direct comparison of different parameter estimation runs.

3.1 Flow Calibration

The initial model runs simulated the pattern of runoff events adequately but did not predict the runoff characteristics well enough. Several optimisation runs with altered parameters were conducted to calibrate the hydrological behaviour of the Currency Creek catchment. To match the event flows and daily peak discharges, the values of CN and rainfall distributions had to be tuned. As could be expected the model responded immediately to changes of CN by producing increased volumes of water. However, the initially specified CN values were already high as they represented the real catchment conditions including irrigation of the cultivated area. This raised a question of the spatial extent of the input data and adequacy of catchment conceptualisation. In order to prevent selection of unrealistically high values of CN, still to improve the match between the observed and the simulated event flow volumes, the entire AnnAGNPS input file was modified to reduce the number of simplifications in catchment characterisation. Consequently, irrigation practices were added to the input file and the turf growing area was separated from the general pasture land. The irrigation rates had to be coarsely approximated, as manual, ad-hoc, irrigation predominates in the catchment. Furthermore, the Irrigation Application Data section is new to the model and does not provide flexible options for manual irrigation.

In addition to the changes to catchment conceptualisation, the originally assigned Curve Numbers were also adjusted to the upper range values. Also, one more set of CN was added to reflect different moisture conditions and management operations of the irrigated areas (the pasture and turf growing farm). The calibrated Curve Numbers were as follows: pasture - 78, irrigated pasture - 82 and cultivated area - 94.

Despite a few simplifying assumptions made in the process of runoff simulation, acceptable goodness of fit was achieved for runoff volumes and peak discharges. The level of calibration was quantified with the coefficient of efficiency [Nash and Sutcliffe, 1970] and the mean, used as measures of degree of model accuracy and distribution of central tendency, respectively. Generally speaking, the acceptance criteria for rainfall-runoff modelling are still very much subjective and may vary significantly from application to application.

The quality of hydrologic predictions was assessed with criteria suggested by Chiew et al. [1993]. They are based on 112 monthly streamflow simulations conducted throughout Australia. According to Chiew's findings flow estimates can be classified as acceptable if they have coefficient of efficiency (E) greater than 0.6 and mean simulated flow is always within 15% of mean recorded flow. The E criterion for event flows was met spatially as the coefficient consistently exceeded the threshold limit for monitored locations in the upper part and at the outlet of the catchment. However, the model did not perform equally well for daily and event-based assessments representing the two temporal scales tested. The highest E of 0.82 was achieved for event flow simulations. The level of calibration for the event flow simulations and the divergence of the predicted data from the 1:1 line are shown in Figure 1.

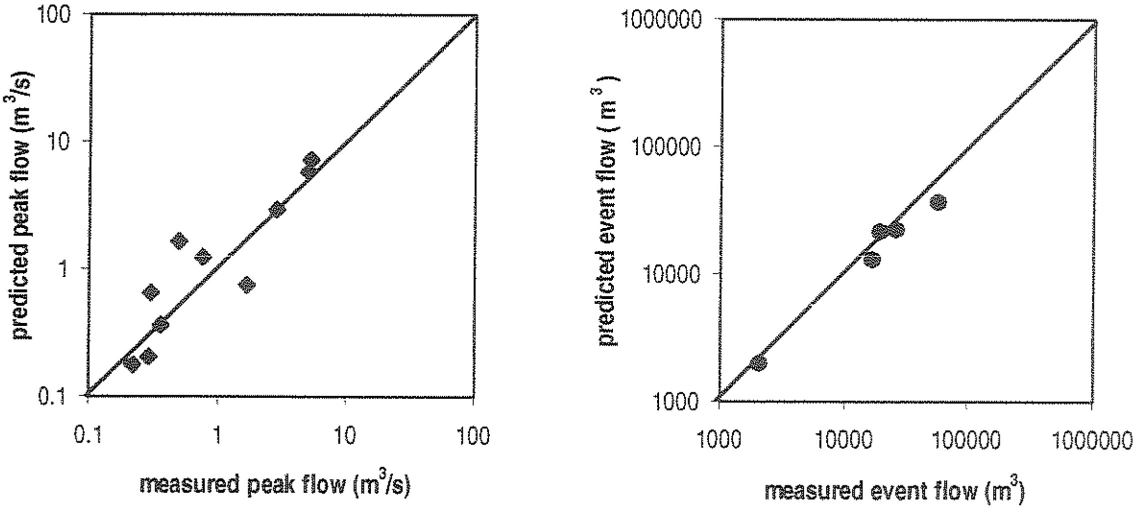

Figure 1. Measured and predicted peak discharges and event flow volumes.

3.2 Optimising Nutrient Loads

Arbitrarily selected 11 input variables representing soil and fertiliser properties were optimised with PEST such that the discrepancies between AnnAGNPS generated daily loads and field measurements were minimised in the weighted least squares sense. The best fit between the observed and the simulated loads was achieved while comparing the results on an event basis rather than for daily predictions (Figure 2). Despite the mean values for the predicted and measured loads matching closely, the coefficient of efficiency (E) was usually negative indicating high deviations of the predicted exports from the measured ones.

Notwithstanding the uncertainty in absolute predictions of nitrogen exports, the model quite successfully simulated the trends in nitrogen generation and relatively close patterns between the simulated and the observed data can be seen in Figure 2. For the events of smaller magnitude the model slightly underestimated nitrogen loads while the opposite occurred for bigger events. This could probably explain the similarities of the simulated and measured mean nitrogen loads which may have resulted from neutralising of opposite sign errors.

Despite noticeable inaccuracies in nitrogen predictions, the results demonstrated a degree of stability and robustness. Phosphorus loads, however, exhibited significant fluctuations during parameter estimation process. Maximum changes were induced by pH perturbations in the top soil layer (pH1 in Figure 3) where pH increase from 4 to 5 could result in reduction in soluble and particulate phosphorus generation by 12 – 25% and 9 – 34% respectively.

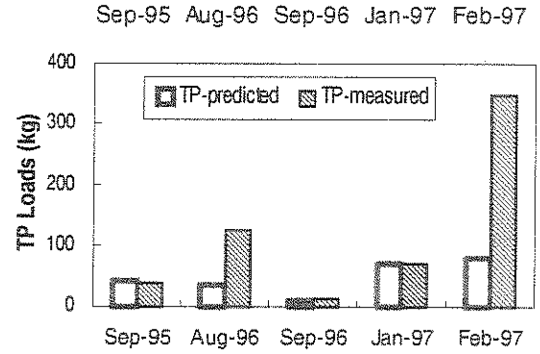

Figure 2. Measured and predicted event loads for Total Nitrogen (TN) and Total Phosphorus (TP).

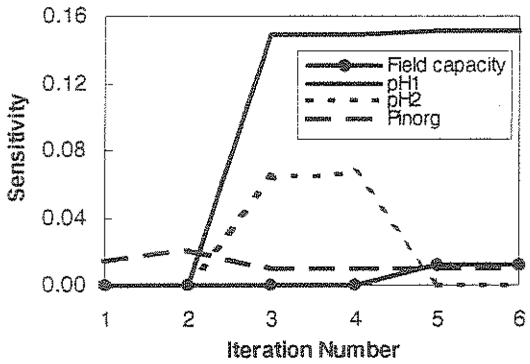

Figure 3. Sensitivity of selected input variables in respect to model generated phosphorus loads.

4. CONCLUSIONS

Evaluation of the model predictions undertaken in this study demonstrates that AnnAGNPS produces results of satisfactory quality when simulating event flows but a high degree of uncertainty is associated with predictions of nitrogen loads. The ability of the model to adequately simulate phosphorus loads in catchments with no permanent flow and multi-peak runoff events is at this stage questionable.

Although popularity of models similar to AnnAGNPS comes to some extent from the fact that they can be applied in data-poor catchments, the need for calibration should be recognised, as it also helps to understand the uncertainty associated with the results and exposes the relevance of parameterisation of the model. Runoff generation and sediment predictions are simulated in the model with separate functions, but nitrogen and phosphorus transport is flow dependent. Therefore, particular attention is needed during verification so the predicted flow volumes match those measured at the gauging stations, if available. Otherwise, any inconsistencies originating from inadequate predictions of the flow volumes and event patterns are likely to be transferred and amplified in the water quality simulations following.

As interdependence of model parameters is evident, calibration can be a difficult process. In order to reduce the time and effort required for calibration of the model, the parameter estimation software such as PEST can be used to guide the selection of input values and to identify the key variables which may have a profound impact on the model outcomes, thus should be evaluated and tuned first. The model input requirements can be very extensive and a considerable amount of time should be allowed for assessment of the initial input data and catchment conceptualisation. A high level of empirical knowledge and, in particular, prior knowledge of the catchment, agricultural activities, soil and climatic conditions, is a big advantage during all phases of modelling.

The observed trends in model simulated nutrient loads indicate that the model may be better suited for larger studies rather than for small subcatchments where local conditions may prevail and over-parameterisation is likely, causing adverse effects on model predictive capacity.

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