Modelling chlorophyll *a* and phosphorus movement to avoid eutrophication in an agricultural catchment

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Abstract: Freshwater eutrophication has been recognised as an important issue related to non-point source pollution (NPS) and agricultural activities. Due the higher costs for monitoring NPS, the necessity to manage nutrient exports from farmland to water bodies and to assess algae growth, mathematic models have become widespread tools to policy-makers and farmers. The Soil and Water Assessment Tool for Geographical Information Systems (GIS) – AVS2000 – model was developed as a river basin scale model to quantify and predict effects from different land management practices in large, complex catchments. The main objective was to assess the phosphorus movement in runoff from farmland to a water body and its implication for degradation of water resources. A chlorophyll *a* model – CHLOA – was developed to simulate algae biomass growth related to total phosphorus (TP) movement in runoff generated by AVS2000 and its consequences to accelerate the eutrophication process. The models were applied to a small catchment of 1.8 hectares at Darnum in West Gippsland, Victoria, Australia. The catchment is in a typical rural area for dairy production which Agriculture Victoria Ellinbank has been monitoring since 1994 to investigate phosphorus transfer from grazed pastures. AVS2000 accurately simulated the flow yield from the site with a Nash-Sutcliffe coefficient (R^2) of 0.99 and a deviation of runoff volumes (D_v) of 5.78 %, after some refinements in the curve number (CN 2). The same response was accurately observed for total phosphorus yielded in the runoff with a Pearson coefficient (r) of 0.99. The CHLOA model simulated the chlorophyll *a* production from 2003 to 2010 under the current management practices at Darnum. The average of the results has classified the water body as hypertrophic, which is expected to impact negatively on the environment and the economy.

Keywords: *Eutrophication; Phosphorus; Runoff; Chlorophyll a; Modelling; SWAT model; AVS2000 model*

1. INTRODUCTION

Over the last decades, water resources have suffered under the pressure of expanding human activity to supply potable water for public supply, power generation, transport, recreation and irrigation. Primary sewage treatment plants were the most important contributors to surface water pollution, until the development of new technologies such as tertiary and quaternary treatment to reduce pollution discharge.

Today, non-point source pollution has become a major factor contributing to water quality degradation. In this scenario, agricultural activities are the principal agent for nutrient and sediment exports, which accelerate the eutrophication process in surface waters. According to Heathwaite and Sharpley (1999), when specialized and intensive farming systems import more nutrient in feed and fertilizer than is output in produce, the result is an increase of nutrient transfer in agricultural runoff.

A change in phosphorus (P) concentrations can disturb the ecological equilibrium in an aquatic ecosystem. Phosphorus, nitrogen (N) and carbon (C) are the principal chemical variables responsible for the acceleration of eutrophication. Eutrophication is a natural process of waters enrichment by inorganic plants nutrient that occurs in many areas around the world but is more common in lentic (lakes) than lotic habitats (rivers). There are different natural pathways to increase nutrients concentrations in waters such as: a) forest fires; b) rock weathering; c) soils erosion; and d) rainfall (transport of P).

Nutrient movement is not an exception in Victoria where some catchments are deeply degraded (Mitchell, 1990). Victoria is a highly productive state in Australia with a large industrial and agricultural production. Mitchell evaluated the environmental condition of Victorian streams and concluded that some streams in the Gippsland region were in very poor condition, with poor bank vegetation (willows or pasture), severe erosion and sedimentation problems. Tiller and Newall (1995) also worked in Victoria and reported that the northwest river region regularly suffers the effect of cyanobacterial blooms, and the south river region (Gippsland) is largely unknown with respect to the effect of nutrients on water quality.

Due to the high costs of monitoring discharges into water bodies, mathematical models have become widespread tools to aid management. The Soil and Water Assessment Tool (SWAT) for Geographical Information System (GIS) is a model developed to predict the effect of different land management scenarios on water quality, pollutant loadings and sediment yield in rural catchments (Srinivasan and Arnold, 1994). The chlorophyll *a* model – CHLOA – was developed based on a local data to express the eutrophication process related to P concentrations in runoff from a Victorian rural catchment.

The aim of this paper is to predict eutrophication in the Darnum catchment, Australia, using GIS-linked modelling based on runoff volume and P concentrations from farmland to avoid accelerating the eutrophication process in West Gippsland.

2. MATERIALS AND METHODS

2.1. Catchment description

The Darnum site (146^{o} 03’ S, 38^{o} 10’ E) is on a tributary of the Moe River in West Gippsland, Victoria, Australia (Figure 1). A paddock with 3.6 hectares was used in this research, which is a rotational grazing area into an intensive dairy farm with 120 ha where approximately 350 dairy cows graze. Roughly a half of the paddock (1.8 ha) is called Darnum and drains to a natural depression on the southern boundary where the runoff was concentrated to a monitoring point by a galvanized iron wall buried 75 mm into the soil.

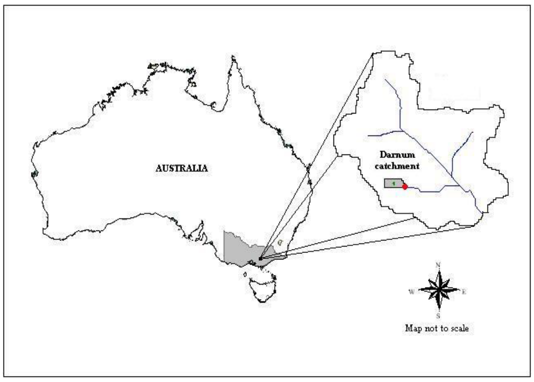

Figure 1. Location of the Darnum site.

The catchment is dominated by dermosols, which are soils with structured B2 horizons more developed than weak throughout the major part of the horizon and lacking strong texture contrast between the A and B horizons (Isbell, 1996). The soil P status measured by the Olsen method increased from 17 mg/kg in 1994 to 55 mg/kg in 1999.

As described by Nash *et al.* (2000), the farmer managed the paddock as part of his normal farm practice, and it received between 60 to 110 kg P/ha annually from 1993 to 1996.

Pastures are the predominant vegetation, amounting to roughly to 95% of the catchment. There are still some areas forested with eucalyptus that form a boundary between different pasture areas. The wetland occupies a small part of the area located near the water channel in the catchment.

The climate of the Darnum site is described as temperate with a mean annual temperature of 18.4 ^{o}C. Summers (December to March) are relatively warm with a monthly average maximum temperature of 23.3 ^{o}C, while winters (June to September) have a monthly average minimum temperature of 5.5 ^{o}C. The annual average precipitation is approximately 1094 mm, more concentrated between May and October.

This area was selected because of the amount of measured data available to compare with AVS2000 outcomes in spite of the small area. Scientists of Agriculture Victoria, Ellinbank have been monitoring this site since 1994 as a part of a program to reduce P exports from farms. Dissolved reactive P (DRP), total reactive P (TRP), total dissolved P (TDP), total P (TP), total dissolved solid (TDS), and total solids (TS) concentrations in runoff have been measured since then. Also, the Bureau of Meteorology of Australia has a meteorological station in the area that has operated since 1960.

2.2. The AVS2000 interface for SWAT 2000

The Soil and Water Assessment Tool (SWAT) is a river basin, or watershed, scale model developed for the Agricultural Research Service in the United States. It is used to predict the impact of land management practices on water, sediment, and agricultural chemical yields over long periods of time in large, complex catchments with varying soils, land use, and management conditions (Di Luzio *et al.*, 2001). Useful results from a non-georeferenced SWAT have been reported for medium and large catchments by different authors such as Srinivasan *et al.* (1993), Peterson and Hamlett (1998), Bringer (1996), and Rosenthal *et al.* (1995).

However, the utility of SWAT is markedly increased by linking it to GIS, which is capable of handling large amounts of attribute data in a spatially reference format. The SWAT ArcView extension is a georeferenced graphical user interface for SWAT model called AVS2000 (Arnold *et al.*, 1998). The GIS interface requires the designation of land use, soil, weather, groundwater, water use, management, soil chemistry, pond, and stream water quality data, as well as the simulation period to run (Di Luzio *et. al.*, 2001). Another valuable land management model that has been linked to a GIS is the Universal Soil Loss Equation – USLE – where the model predicted erosion among different landuses, slope positions and soils taxonomic group (Ranieri *et al.,* 2002 and Lufafa *et al.* 2002).

Input data

To create a SWAT dataset, the interface needs to access ArcView map themes and database files, which provide information about the catchment. The necessary maps and database files were prepared prior to running the interface (Di Luzio *et. al.*, 2001).

Inputs including a digital elevation model (DEM), grid or shape files of land cover / land use, soil, precipitation data, temperature data, solar radiation data, wind speed data, relative humidity data, soil physical and chemical data, weather generator, and management practices were used to run the model. The meteorological database from the last thirty years (1971 – 2000) was provided by the Bureau of Meteorology of Australia, and used in this research to calibrate the model and get more accurate outcomes.

Tests of model performance

The Nash-Sutcliffe coefficient (R^2) and the Deviation of runoff volumes (D_v) were applied to the runoff as a basic test of goodness-of-fit recommended by the World Meteorological Organization – WMO – for hydrological model performance (ASCE, 1993). The Pearson correlation coefficient (r) and its squared (r^2) were used to analyse the total P concentration exported in the runoff.

***Nash-Sutcliffe coefficient* (R²)**

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_1)^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \quad (1)$$

Where Q_i is the measured yearly discharge, Q'_1 is the model-simulated discharge, $\bar{Q}$ is the average discharge for the simulated period, and n is the number of discharge values (Nash and Sutcliffe, 1970). The R^2 can vary from 0 to 1, with 1 indicating a perfect fit (ASCE, 1993).

The deviation of runoff volumes (Dᵥ)

$$D_v = \frac{\sum_{i=1}^{n}\left(Vi - V'_i\right)}{\sum_{i=1}^{n} V_i} * 100 \quad (2)$$

Where Vi is the measured yearly runoff, V'_i is the simulated yearly runoff volume and n is the number of years (Martinec and Rango, 1989). Dv can take any value; however, the smaller the number the better the model results are. Dv would equal zero for a perfect model (ASCE, 1993).

2.3. Modelling Chlorophyll *a* – CHLOA

Chlorophyll is the major light-absorbing pigment in green plants that absorbs sunlight and uses its energy to synthesise carbohydrates from CO_2 and water in a process known as photosynthesis. Chlorophyll *a* is a measure of the portion of the pigment that is still active, which is used to indicate the amount of phytoplankton present in water bodies. Chlorophyll *a* is considered the principal factor to use as a trophic state indicator in water. There is generally a good relation between planktonic primary production and algal biomass that is an excellent trophic state indicator.

Chlorophyll *a* is the single most responsive indicator of P and N enrichment in aquatic systems. As concluded by Kalff (2002), the empirical relationships between phosphorus-chlorophyll *a* are widely known and been used to manage lakes, rivers and catchments all over the world.

The mathematic model was developed based on the average of TP concentration (µg/L) in summer and the average of annual chlorophyll *a* (µg/L), which represent the better correlation between the two factors for the assessed area where $R^2 = 0.92$. The equation was defined as:

$$[Chl] = \frac{7.3 * \left(p^{1.45}\right)}{100} \quad (3)$$

Where (p) is the average TP concentration in µg/L, 1.45 is the slope of the regression curve and 7.3 is the intercept value for the regression.

3. RESULTS AND DISCUSSION

Runoff

Runoff generated by the AVS2000 model is based on the Soil Conservation Service (SCS) runoff equation, which was developed in the 1950s for estimating the runoff yield from rainfall for a variety of soil types and land use conditions of a catchment (Rallison and Miller, 1981). The SCS curve number (CN) is a function of soil's permeability, land use and antecedent soil water conditions for dry soils while CN2 represents the average soil moisture conditions (Neitsch *et al.*, 2000).

As the primary variable that affects the runoff outcomes, the CN2 value in the model can be modified until the model predicts runoff accurately, where small CN2 values mean less surface runoff from farmland. The model automatically sets up the CN2 value based on a hydrological soil group from soil profile properties and a wide variety of land covers, such as pasture, woods and cereal crops. The curve number can be affected by the slope and soil properties such as depth to seasonally high water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer (Neistch *et al.*, 2001).

Outcomes from the model simulation from 1994 to 2000 were not accurate when compared with the observed database when the hydrologic soil group and pasture defined the CN2 curve as 86 (Fig. 2). The model was over-predicting the runoff as seen in the analyses where the Nash-Sutcliffe coefficient was 0.48 and the Dv = – 61.8 %. The negative value from the Dv analysis showed that the amount of runoff predicted by the model was not accurate and much more surface runoff was yielded than the observed runoff.

As the initial CN2 values were based on a slope of 5%, an adjustment was made to suit the 8% slope from Darnum where the CN2 curve was adjusted to 51 and the model performance was much better than all the previous simulations (Fig. 2). However, some adjustments in the soil water capacity value (SOL_AWC) were also necessary to refine the model's achievement. The statistical analyses confirmed the improvement and accuracy of the model after the CN2 and SOL_AWC input adjustments where the Nash-Sutcliffe coefficient was 0.99 and the Dv = 5.78 % (Figure 2).

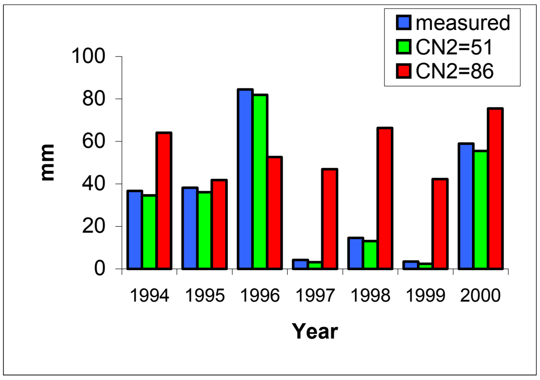

Figure 2. Simulated and measured runoff from Darnum site with CN2 values of 51 and 86.

Total phosphorus (TP)

Many model variables such as nutrient concentrations in the soil, fertilizer applications, tillage operations and biological mixing efficiency can affect the model's simulations of using the calibrated runoff, the second step ran on the AVS2000 simulation to predict the TP concentration in runoff from the Darnum catchment to a water body. All necessary variables to simulate TP loss were input to correctly run the model. Nevertheless, the initial outcomes showed that the model was under-predicting the TP exports from Darnum site (r^2 = 0.69).

As a factor that can change nutrient concentrations in runoff, the biological mixing efficiency – BIOMIX – acts with the same characteristics as a tillage operation, which incorporates residue and nutrients into the soil (Neitsch *et al.*, 2000). As described by Neitsch *et al.* (2001), biological mixing is the redistribution of soil constituents as a result of the activity of biota in the soil (e.g. earthworms, etc.) and shows a significant increase in systems where management shifts from conventional tillage to conservation tillage to no-till.

As described previously, Darnum site has a conventional management practice, which increases the BIOMIX value and the P concentration in soil. Therefore, some adjustments were made to get more efficiency in the BIOMIX variable that was 0.20 as a default value during the previous simulations and was set to 0.60 on the final running. The new BIOMIX value produced a more accurate and acceptable output when compared with the observed data at the Darnum site (Figure 3).

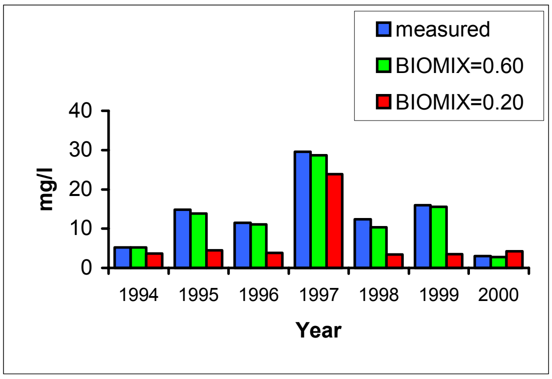

Figure 3. Total phosphorus (TP) concentrations from Darnum under different biological mixing efficiency – BIOMIX – values.

Chlorophyll a

The CHLOA was applied to calculate the chlorophyll *a* production under the current conditions at Darnum. The results provided from AVS2000 to runoff and TP concentrations were inputted in the model to simulate chlorophyll *a* from 2003 to 2010 considering the existing management at Darnum.

The outcomes generated by CHLOA showed that if the currently management were kept at Darnum, the chlorophyll *a* production would vary between 31.2 µg/L to 271.7 µg/L with an average of 107.9 µg/L (Figure 4). Those values of chlorophyll *a* can classify the water body between mesotrophic to hypertrophic based on the trophic system proposed by Ryding and Rast (1989). The chlorophyll *a* average from 2003 to 2010 was 107.9 (µg/L), which has classified the aquatic system as hypertrophic.

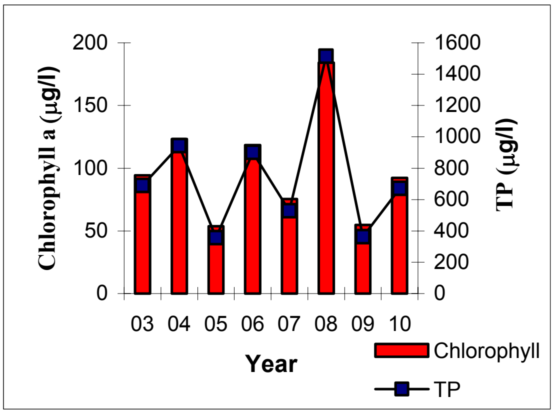

Figure 4. Simulated chlorophyll *a* production and TP concentration for Darnum.

4. CONCLUSIONS

Despite previous applications of other versions of the SWAT model to large and complex catchments, the Geographical Information System (GIS) version of SWAT 2000 – AVS2000 – has been successfully applied to a small catchment in Victoria, Australia.

The statistical analyses of the runoff outcomes from the model confirmed its prediction accuracy. The Nash-Sutcliffe coefficient for the final run was R^2 = 0.99, while the deviation of the runoff volumes (Dv) was 5.78% after adjustments had been made. The total phosphorus (TP) concentration predictions needed fewer adjustments than the runoff simulations did, due to the relationship between the concentration of TP and the runoff yield. The initial outcomes from the model were over-predicting the TP concentrations in the runoff. Some necessary refinements were done on the BIOMIX input to increase the AVS2000 execution. The coefficient of determination substantiated the model's performance where the outcomes achieved an R^2 = 0.99 after the final calibration.

The GIS interface is a friendly environment that keeps the user attention due the graphical resolution and model options. The outcomes showed that the GIS interface is capable of simulating concerning runoff, TP and chlorophyll *a* dynamic interactions that occur inside a catchment, as described for the CN2 curve and the BIOMAX values, trustful and accurate due its large database, digital maps and digital models.

The CHLOA model results showed that if the currently management practices such as P fertilizer application will be maintained, the eutrophication process will be able to accelerate quickly with environmental and economic prejudices to the region. The CHLOA model can be considered a powerful tool integrated to AVS2000 to manage P in farmland and to avoid accelerating the eutrophication process.

5. ACKNOWLEGMENTS

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