Terrestrial nutrient cycling, transport and vegetation dynamics

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1.1 Executive Summary

This report aims to present a detailed literature review of the transport dynamics and mechanisms for nutrients moving within the terrestrial landscape. The nature of the review is directed to assist in the development of catchment management strategies and simulation model implementation as a significant tool in the future development and assessment of current catchment management practises. The Victorian terrestrial environment is coming under increasing pressures due to continuous agricultural and urban developments and predicted impacts of climate change. It is therefore vital that landscapes are viewed as whole ecosystems, and hence, models used to predict and simulate impacts of activities within catchments must capable of predicting the implications of climate change and land use at appropriate temporal and physical scales. For the purpose of this report a catchment is defined as a geographic area that is drained by rivers, streams and its tributaries. Land use and classifications within a catchment can be agricultural, native vegetation or urban, or a combination of one or more of these land use types. A review of the relevant scientific literature revealed that there are significant gaps in knowledge pertaining to fertiliser application (rates and quantity) in Victorian agriculture and a very limited amount of information regarding the nitrogen and phosphorus plant tissue concentrations for all the species considered in this report.

After a confined yet detailed examination of the Soil & Water Assessment Tool (SWAT) version 2005, the conclusion has been reached that SWAT provides a suitable framework for modelling catchment processes (specifically focused on terrestrial nutrient cycling) that are essential for best management practise, and were noted as important and required components in discussion with the Department of Sustainability and Environment (pers comms Mark Eigenraam, Wayne Lewis). Consequently we consider SWAT to be well suited to modelling and simulating terrestrial nutrient cycling, transport and vegetation dynamics for catchment management in the Victorian region. While validation has not been undertaken, the equations in the model consider the relevant major processes, which, based upon this review, account for the dynamic interactions between the water and soil environments and the movement of nutrients within the terrestrial system. The recommendation of using SWAT within the EnSym framework should, however recognize the significant gaps that have been identified in the SWAT model, all of which should be included in a model framework if it is to effectively address the environmental conditions and challenges that are presented to catchment management authorities. Furthermore, it is important to note that the impacts and affects of drought, salinity and fire prone environments, all of which are intrinsic to the Victorian landscape, are not addressed in the SWAT model. Another element of the SWAT model that must be altered to suit Victorian ecosystems are the groundwater and tree growth model components of SWAT, which must be modified to enable a water balance modelling with greater accuracy in Australian catchments. It

is recognised that groundwater modelling is currently under detailed research and investigation for the Victorian catchments, however, once the appropriate data has been collected a detailed examination of the groundwater equations and conceptual theory held within the SWAT model must again be thoroughly examined to ensure that the equations account for the nutrient flows and transport mechanisms that are linked to groundwater systems. As with any model, there is a great need for extensive peer review and validation of the model, the capabilities and applicability of the equations and theory to the environment under question. Ongoing refinement and re-evaluation of the model's suitability to the selected environment and modelling task objectives are also extremely important as new models and updated versions of different frameworks become available. Other models could successfully be incorporated or maintained in the EnSym framework to account for the inadequacies found in SWAT to address the issues of drought, salinity and the impacts of fire to nutrient transport and cycling in the terrestrial ecosystem. The major limitation that has been brought to our attention during the preparation of this review is the minimal validation of the SWAT model for Australian ecosystems. Validation of the model has been undertaken in both Europe and the United States of America; however this review only identified two papers that address the validation of the SWAT model for Victorian landscapes (Watson *et al.*, 2003, Watson *et al.*, 2005), and a total of four studies in Australia . Recognising the limitations outlined in this report, we conclude that the SWAT model is well suited for use in the EnSym framework, however its usability is provisional to the availability of sufficient data inputs to run the equations within the modelling framework.

1.2 Scope of the report

This report begins with a review of the major nutrients nitrogen and phosphorus in the terrestrial ecosystem providing background information (2.2 Major nutrients in terrestrial ecosystems) for increasing the understanding of the dominant modes of nutrient transport and the effects of such mechanisms within a terrestrial ecosystem to further develop catchment management modelling systems (2.3 Transport of key nutrients within the Australian landscape). These components include the transport of N and P via surface and subsurface pathways and a discussion on the affects of agricultural activity on these transport pathways. The nutrient (N & P) content of plant tissues is detailed, examining reference crops of wheat (*Triticum durum* and *Triticum aestivum* L.), barley (*Hordeum vulgare*), pastures such as White Clover (*Trifolium repens*), Subterranean Clover (*Trifolium Subteraneum*), Phalaris grass sp. (*Phalaris aquatic*), and Perennial Rye Grass (*Lolium perenne*), a generalized tree (seedling, juvenile, mature) of *Pinus radiata* and *Eucalyptus globulus*, a stand of trees, and a typical plant tissue nutrient content of N and P using tomatoes (*Solanum lycopersicum*) as a reference crop (2.4 Nutrient (N & P) requirements of plants).

A detailed examination of the Soil & Water Assessment Tool (SWAT) is undertaken (2.5 Review of the SWAT model and current use/limitations), reviewing in brief the history and development of the model, and extensively discussing and evaluating the major components of the modelling framework focussing on nitrogen, phosphorus, nutrient transport, land cover/plant growth and soil hydrology. We then extend this review to consider the mathematical equations

held within the SWAT model, focussing on the capabilities, limitations and advantages of the equations. In this section we provide a review and evaluation of each equation and/or concept, commenting on whether or not the model equation has been peer reviewed, or in the absence of such review, comment on the terms included in the equation.

Our review of SWAT and through ongoing consultation with Mark Eigenramm and Wayne Lewis lead to our inclusion of a tabulated review of the most commonly used and available catchment models. We present a tabulated review of the available model frameworks available, with special attention to models that function on a daily time-step, and include extensive capabilities for modelling nutrient transport in terrestrial ecosystems. The tabulated review is not an exhaustive list of available models given the time constraints of the project, however the model included in the table are ones that address the requirements outlined in discussions during the consultation period (pers comm. Mark Eigenramm, Wayne Lewis) or are submodels that account for gaps that were identified in the SWAT model. From this analysis emerges an understanding of potential model shortcomings, identify key knowledge gaps within the SWAT model and other available models, locate research priorities for the validation and improvement of the SWAT model, and provide recommendations for future modelling requirements.

Finally, we synthesise the major findings of the review, identify key knowledge gaps, and present research priorities that need to be addressed to effectively incorporate SWAT and other selected models into the EnSym framework (Section 3. Knowledge gaps and future needs).

Section Two – Literature Review

2.1 Introduction

Victoria is a geomorphologically diverse landscape, incorporating coastal plains and dune systems, floodplains, volcanic and alluvial regions, mountains, waterways and tributaries, estuaries. Victoria is extensively used for agriculture including cropping (cereals) and livestock grazing (beef cattle, sheep and dairying). Victoria also has large eucalyptus forests, as well as pine and eucalyptus plantation, mining, residential and highly urbanised areas (Watson *et al.*, 2003). Environmental management frameworks must aim to incorporate modelling components that have the capacity to account for this diversity in land use and vegetation types to ensure the implementation of best management practises in the Victorian terrestrial environment.

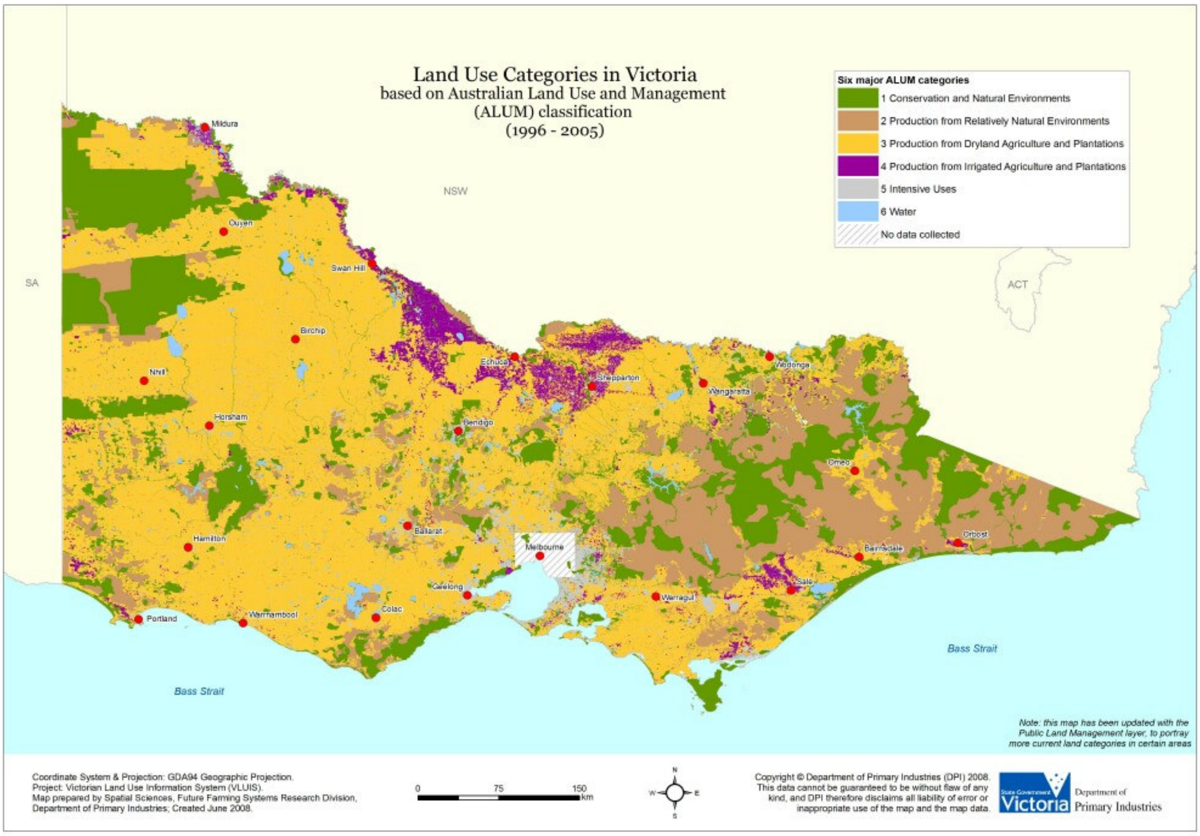

Figure 1. Land use in Victoria, based on Australian land use and management classification (1996-2005), taken from the Department of Primary Industries (DPI, 2009). Formal permission not sought.

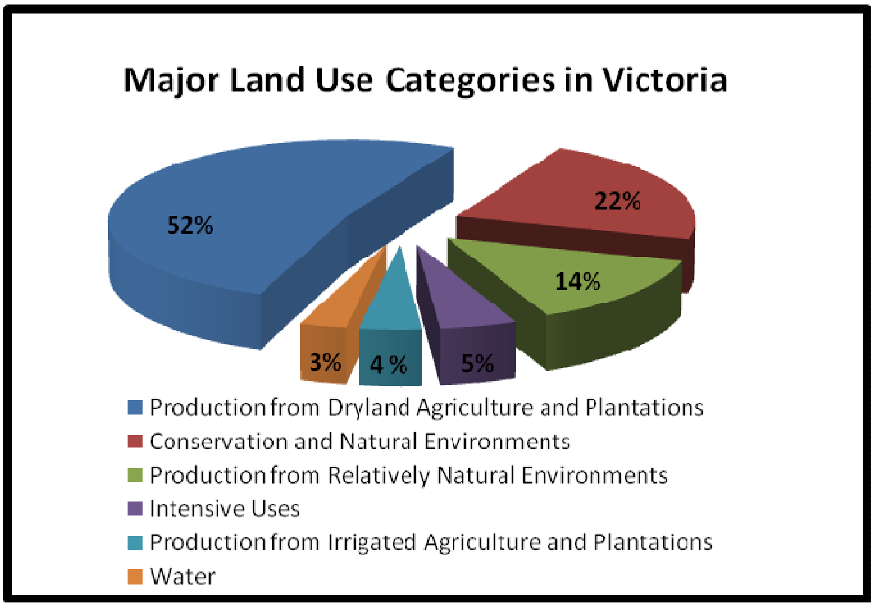

Figure 2. Victorian land use (DPI, 2009). No formal permission sought.

Modelling terrestrial nutrient cycling (transport and export) at a catchment scale enables predictions for potential environmental impacts of future events and trends (e.g. impacts of climate change). A model, for the purpose of this report, is defined as a mathematical method to estimate water quality and the transport of substances (nutrients, sediments, and pollutants) which is based on various theoretical assumptions and generalizations (Arheimer & Olsson, 2003). Models can be divided into three types, dynamic, mechanistic and conceptual. Dynamic models are commonly used to evaluate and simulate processes at a catchment scale, and include both *mechanistic* and *conceptual* models. Mechanistic models are those that use the biological, chemical and physical laws to describe process using mathematic grids. Conceptual models describe flow paths using empirical data taken from numerous sub-basins, coupling them to account for the hydrological heterogeneity of a single catchment regions, for which average conditions are described (Heng & Nikolaidis, 1998, Nicks *et al.*, 1984). Conceptual models are more effective for the application to large scale studies or regions where data is sparse, as they demand less input data and conceptual effort whilst accounting for processes occurring in the catchment (Arheimer & Olsson, 2003). Numerous models are available to catchment management authorities (CMA), which can be attributed to the multi-disciplinary nature of this field, inclusive of a broad spectrum of scientific backgrounds and interests. Data collection for these models is commonly carried out on small scales such as fields or plot based studies with results extrapolated to represent regions, basins or entire catchments (Shirmohammadi *et al.*, 2005). Realistic modelling of terrestrial nutrient cycling in large catchments requires a certain level of measured data (Hejzlar *et al.*, 2009). This limits the accuracy of many models, constraining the outputs, and potentially undermining the modelling capacity to quantify the true state of the landscape and the predictive abilities at the required spatial or temporal scale (Shirmohammadi *et al.*, 2005). Nutrient loading and sediment transportation are one of the many

environmental components that Australian CMAs must incorporate into management frameworks. The impacts of terrestrial nutrient cycling must be considered when assessing the sustainability and quality of freshwater systems. There are several deleterious effects of increased nutrient loadings within a catchment on receiving waters. These include increased biomass of freshwater phytoplankton and periphyton, elevated pH, depletion of dissolved oxygen in the water column and reduced water clarity (Newham *et al.*, 2004).

Nutrients play a vital role in determining soil fertility and the resulting vegetation cover of a landscape. As the nutrients that most commonly limit plant growth, nitrogen and phosphorus are the two key nutrients that will be the main focus of this report. Nitrogen and phosphorus are essential for plant growth, determining establishment and growth rates, and are required in different quantities for different species (Lines-Kelly, 2002, McKenzie *et al.*, 2004). Consequently, large quantities of both nitrogen and phosphorus fertilisers are applied to agricultural regions to enhance productivity. Nutrients are transported by flowing water within soil solution, and are exported from one landscape to another via transportation mechanisms, surface and subsurface flows (Section 2.2). Nutrient additions of nitrogen and phosphorus are often applied to agricultural landscapes in the form of fertilisers. Excess nutrients are lost or transported within the terrestrial ecosystem to other parts of the environment by leaching, runoff, erosion, mineralization and decomposition (Mosier *et al.*, 2004b, Strong & Mason, 1999, Liao *et al.*, 2008). Nutrient movement within the terrestrial environment is difficult to model due to the complex interrelated nature of nutrient transport and flows within the soil profile and transport within the catchment. Movement between the soil profile, vadose zone, shallow and deep aquifers, and transport to channels, streams, and tributaries are difficult to accurately model. Accounting for all the environmental variables that impact these processes can lead to extremely complex empirical models that may not in fact be a true representation of the landscape processes.

The following sections provide a review of the dynamics and transport mechanisms of nitrogen and phosphorus in the terrestrial ecosystem, following with a detailed analysis of the nutrient requirements of plants focusing on reference crops of wheat (*Triticum durum* and *Triticum aestivum* L.), barley (*Hordeum vulgare*), pastures such as White Clover (*Trifolium repens*), Subterranean Clover (*Trifolium Subteraneum*), Phalaris grass sp. (*Phalaris aquatica*), and Perennial Rye Grass (*Lolium perenne*), a generalized tree (seedling, juvenile, mature) of *Pinus radiata* and *Eucalyptus globulus*, a stand of trees, and a typical plant tissue nutrient content of N and P using tomatoes (*Solanum lycopersicum*) as a reference crop.

The remainder of the report will focus on the analysis of catchment modelling frameworks, specifically examining the SWAT model and comparing this models ability to successfully represent and simulate the Victorian landscape processes with other available models. Models that have been considered extensively in this report run on a daily time step and have the ability to model soil hydrology, nutrients and nutrient transport, and land cover/plant growth. Models are limited by data availability, temporal and spatial resolution, complexity and breadth of

scenarios that they are able to model and simulate. However, regardless of how all encompassing a model may appear, without sufficient application, evaluation and validation, we recommend models should not be utilised for catchment management without due caution. Validation of a model ensures that the equations and theory behind the equations held within the model are applicable and appropriate to the landscape and environmental conditions for which the model is being employed. This is especially important for models used in terrestrial ecosystems due to the spatial heterogeneity of soil.

The EnSym framework, currently used by the Department of Sustainability and Environment, incorporates several scientific models to improve our understanding of the impacts of management actions on a landscape. The models used within this framework require extensive evaluation and validation to ensure that they are the best models for the required modelling tasks, and meet useability and accessibility requirements. To ensure that the best models are selected for the EnSym framework it is vital that all possible models are investigated, comparisons drawn and a final evaluation made to best advice on the models for the EnSym framework. This report provides a tabulated review, to the best of our knowledge given the availability of information, of the available scientific models currently used worldwide to select the best models for use within EnSym.

2.2 Major nutrients in terrestrial ecosystems

2.2.1 Nitrogen

Background: Nitrogen in terrestrial systems

The availability of nitrogen is vital for, and largely controls plant growth as it is required for protein assimilation. The nitrogen range of Australian soils usually lies between 0.02-0.5 %, broadly correlating with the organic carbon levels of a the soils, and consequently the rainfall and temperature specific to the region (McKenzie et al., 2004). Nitrogen is primarily derived from soil and plant litter or from nitrogen additions to the soil. Nitrogen additions to the terrestrial system occur via fertiliser application, crop inputs through biological N-fixation, recycling of N from crop residues, animal manures, atmospheric deposition, and irrigation water. The majority of N supplied from the soil is in the organic form and is released through microbial processes into mineral forms such as ammonium (NH_4^+) and nitrate (NO_3^-). Nitrogen is removed from soil by plant uptake, leaching, erosion, denitrification and volatilization (Neitsch *et al.*, 2005).

Under cropping, approximately half the N is removed from the field during harvest, causing a significant N loss in the system. The remaining N is incorporated into soil organic matter or is lost or transported within the terrestrial systems. This occurs via leaching under heavy rainfall or irrigation, runoff and erosion, ammonia volatilization, mineralization, and denitrification/nitrification (Mosier *et al.*, 2004b, Strong & Mason, 1999).

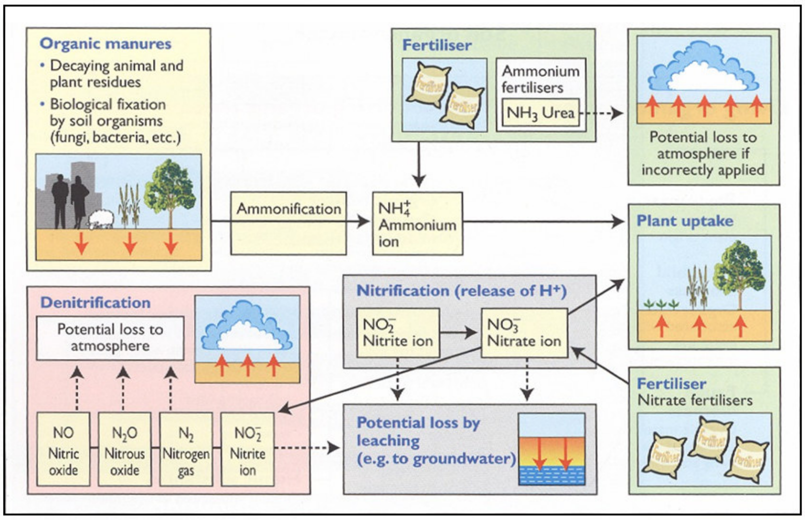

Figure 3. The terrestrial nitrogen cycle. Sourced from McKenzie *et al.* (2004). Formal permission not sought.

Both leaching and crop removal can cause serious problems for maintaining the nitrogen supply in a cropping system (McKenzie et al., 2004). Processes of nitrogen loss and movement in a terrestrial environment are influenced by ecosystem type, soil properties, regional climate (temperature and rainfall), and cropping/agricultural and management practices e.g. fertiliser application regimes and irrigation practices. Different cropping techniques and seasonality of crop type region by region can also influence the rate, total quantity and pathway of nitrogen loss, and can vary significantly over small areas, even within a field due to the heterogeneous nature of soil characteristics (soil texture, soil moisture). Nitrate leaching and denitrification are the main pathways via which N is lost in Australian terrestrial (specifically agricultural) systems (Mosier et al., 2004b). Denitrification is more commonly observed in poorly aerated, wet or waterlogged soils. Periods of soil saturation due to heavy rainfall or irrigation over slow draining soils can result in reduced soil mineral N levels due to the conversion of soil N into gaseous N forms (N_2 and N_2O), which are lost to the atmosphere. Leaching of nitrate deeper in the soil profile beyond the root zone is more commonly observed in regions subject to heavy rainfall or intensive irrigation. Soils with rapid internal drainage such as sands and loams are more prone to nitrogen loss via leaching than fine textured soils such as clays (McKenzie et al., 2004).

The loss of nitrogen in many Australian soils has occurred as a result of poor management (e.g. excessive application) in horticultural and agricultural systems, and varies with soil and crop type. Understanding and controlling nitrogen leaching and effluent disposal from agricultural landscapes is a major challenge, as excess nitrate in a hydrological system is ecologically harmful. Better management practices are required to reduce the over-application of N-fertilisers and the resulting risk of groundwater and land contamination (Strong & Mason, 1999).

2.2.2 Phosphorus

Background: Phosphorus in terrestrial systems

Phosphorus is essential for all plant growth during the early development phase and is, especially important in agricultural cropping systems. Plants, in agricultural cropping systems need phosphorus to help bridge the gap between the exhaustion of seed phosphorus reserves and the development of root systems to access phosphorus in the soil. Phosphorus is an important constituent of plant cells, and is essential for cell division and development of the growing tip of a plant. For this reason it is vital for seedlings and young plants (Lines-Kelly, 2002). Phosphorus can enter into the terrestrial systems from atmospheric deposition, eroding surface and subsurface soils, fertiliser application and the decay of organic matter (Young *et al.*, 1996). However, plant species and different genotypes can vary significantly in their ability to obtain phosphorus from the soil and surrounding environment for biomass production (Liao *et al.*, 2008).

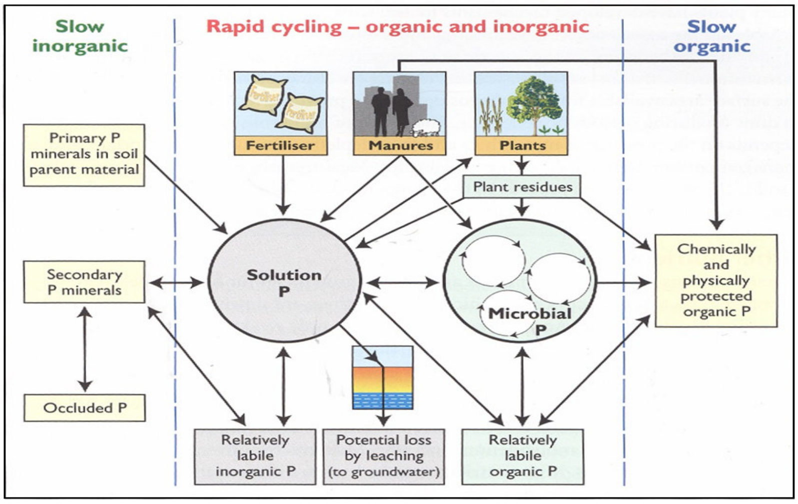

Figure 4. The terrestrial phosphorus cycle. Sourced from McKenzie *et al.* (2004). Formal permission not sought.

Australian soils are typically low in plant-available phosphorus, therefore fertilisers are applied in cropping systems to soils to attempt to improve phosphorus efficiency, and hence, optimise crop growth to obtain maximum crop yields. Phosphorus fertiliser application is considered optimal in a cropping system when the amount of P applied is equal to that which is removed in crop harvest (Liao et al., 2008, Helyar, 1998). Excessive phosphorus fertiliser application is unnecessarily expensive and can results in environmental problems caused by runoff and leaching of excess phosphorus into the surround environment (Liao et al., 2008). Thus, both economic and environmental gains are to be made through more efficient phosphorus use.

2.3 Transport of key nutrients within the Australian landscape

Transport of nutrients refers to movement by flowing water (drainage) after mobilization, whilst nutrient export refers to the transfer of nutrients from one landscape compartment such as soil to another, such as a lake, stream or reservoir. Mobilization of nutrients refers to the movement of a nutrient through dissolution in water or the detachment of soil particles and colloids and associated nutrients (Mathers *et al.*, 2007). Section 2.3.1 will review the dominant modes of nutrient and sediment transport across landscapes: *surface* and *sub-surface* flows.

Land use heavily alters several environmental attributes which influences nutrient transport within a landscape. Several factors are considered important in determining nutrient transport mechanism such as soil type, geology, drainage capacity, rainfall, catchment size, topography and current and historical land management practices. Nutrients are transported through a terrestrial ecosystems by surface and sub-surface flows, and also by wind translocation (Young et al., 1996, Neitsch et al., 2005). Flows through subsurface or surface pathways depend on factors such as landform, soil infiltration rates, and the sorption characteristics of soil layers within the soil profile (Mathers et al., 2007). In the context of catchment management,

understanding the movement of nutrients within the terrestrial ecosystem and the links and follow-on effects on waterways are extremely important given the input/additions of nutrient fertilizers in agro-ecosystems and their potential to mobilize and leach into the surrounding environment (Drewry et al., 2006). The degree to which the different nutrient flow paths are responsible for the mobilization and transport of nutrients depends on the physicochemical properties of the soil, such as the infiltration depth and the distribution of nutrients with depth and within a particular soil depth (Mathers et al., 2007).

Point source and non-point source nutrient and sediment pollutants in catchments

Point source nutrients and sediments are readily identifiable inputs such as directly discharged sewage water or industrial waste products released into rivers and ocean. Non-point sources of nutrients and sediments refer to those inputs occurring over a wide area and are associated with particular land uses, as opposed to individual point source discharges. In agricultural catchments non-point sources include pesticides, fertilisers, animal manure and soil washed into streams in rainfall runoff. In heavily stocked riparian agricultural regions, water may degrade faster and erosion be accelerated causing increased sediment and pollutant loadings to stream and river systems. The forestry industry also contributes to non-point sources of pollution by increasing erosion and sediment runoff caused by soil destabilization from tree removal. In an urban landscape or catchment, non-point sources are commonly observed as seepage and surface runoff from septic tank effluents or rainfall runoff from street surfaces contaminated with car oil, lead from petrol, soil and sediment runoff from construction sites, and faeces from domestic animals (EPA, 2009).

2.3.1 Review of dominant modes of nutrient (N & P) transport across landscapes

Surface flow nutrient transport

Surface flow is the dominant mode of transport for particulate-bound nutrients like phosphorus and some forms of nitrogen. Surface or overland flows of nutrients are primarily determined by rainfall events and occur via pathways of erosions and runoff. Rainfall characteristics such as rainfall intensity, rainfall depth, drop size and time since last rainfall are important in determining the extent and severity of surface flows of nutrients; however, most reported studies on rainfall impacts on nutrient loss and translocation are generally based on soil erosion studies (Young et al., 1996). Surface runoff is also strongly influenced by soil-plant systems, determining the risk of wind and water erosion of the soil through the binding of soil particles by plant root systems and ground cover protection e.g. the quantity of unattached deposited materials available for translocation or degree of vegetative cover. Wind erosion can also be a significant process of nutrient translocation in the Australian landscape, however aeolian nutrient transport is more episodic compared to surface runoff (McKenzie et al., 2004). Topography influences nutrient surface flow, with land slope affecting the velocity of surface runoff which determines the erosive power and transport capacity (Young et al., 1996). Large flooding events are often responsible for the transportation of high sediment and nutrient loads, and can pose significant environmental problems for both the regions of removal and deposition (Drewry et al., 2006). Nutrients can move over or through the soil surface under the action of three main mechanisms: infiltration-excess overland flow; interflow, or saturation-excess overland flow. Infiltration-excess overland flow occurs when water on the soil surface as rainfall or irrigation exceeds the infiltration capacity of the underlying soil, causing runoff of nutrients and transport through the catchment. Interflow is the lateral movement of water through surface soils. In cases where subsurface flows are restricted by soil physical properties such as restricted drainage ability, nutrients move through soil inter-layers. When the soils surface is naturally impermeable or impermeable due to soil management (cropping and agricultural practises) and water drainage/infiltration into soil is not possible, saturation-excess overland flow will occur. The saturation of soil surface layers is particularly common in Victorian texture contrast soils where soil compaction has occurred (McKenzie et al., 2004). All three processes of overland or surface flow of nutrients results in what is commonly referred to as “surface runoff”. It is common to observe all three processes occurring concomitantly (Mathers et al., 2007).

Sub-surface nutrient transport

Sub-surface nutrient transport occurs through processes of catchment groundwater discharge, leaching and soil drainage. Soil type strongly affects these subsurface nutrient transport mechanisms. Inevitably, nutrient content of the soils determines the preliminary potential for nutrient export (derived from soil parent material), whilst nutrient additions to a landscape under

different land management practices will alter the nutrient load that flows through the subsurface transport/export pathways. Soil type determines the nutrient adsorption capacity of a soil which affects the nutrient (organic and fertiliser) storage capacity, which inturn will influence surface runoff nutrient levels (Young et al., 1996). Soil structure directly influences water infiltration and susceptibility and resistance capability to erosive processes and overland flows. Nutrient loss and transport by subsurface flows is likely to be higher in sandy highly permeable soils compared to clay soils that are characterised by low permeability for which surface flow nutrient transport are more typically observed. However, clay soils typically have a higher nutrient load and therefore have a greater loss potential. Cultivated and intensively managed soils differ significantly in nutrient storage capacity and hence nutrient loss potential.

Topographic variation within a catchment, including land slope, drainage density and catchment size, all influence nutrient transport. Soil permeability or drainage density determines the accession rate at which nutrients flow from the soil to waterways. Intensively managed agricultural landscapes in Australia are often highly eroded with increasing drainage density resulting in elevated nutrient loss and transport to waterways through subsurface soil flows (Young et al., 1996). Matrix flow and macropore flow are the two mechanisms by which nutrients move through subsurface pathways. Matrix flow (saturated-excess overland flow) occurs in highly permeable soils, and is a very important nutrient transport pathway. Matrix flow results in the export of N, and in low P retention soils there is also the potential for P export. Macropores are the internal channels in soil that facilitate the movement of water and dissolved materials through and within the soil profile (Mathers et al., 2007).

Impacts of agricultural activity on terrestrial nutrient transport modes

Activities such as vegetation clearing, tillage, and grazing cause the breakdown of soil aggregates, degrading the soil structure. Soil aggregate breakdown can result from raindrop impact on bare soils (clear-cut or bare-fallow), compaction and shear by machines and hoofed animals, a loss of organic matter (removal in harvest), irrigation with high Na^+ water, and a loss of soil micro-organisms. Structural degradation of soils as a result of agricultural activity causes problems such as hard-setting or surface crusting (loamy soils), compression (clayey soils), reduced infiltration, excessive runoff, erosion and poor plant growth (reduced gas exchange, less available water, reduced root penetration capability). The degradation of soil structure is also inversely related to soil carbon. The disturbance of soil under tillage, vegetation clearing and other agricultural practises lead to a reduction in soil carbon retention and results in a further breakdown of soil aggregates (Yang *et al.*, 2007). Soil chemical fertility decline is caused by the reduced capacity of soils to hold nutrients (reduced cation holding capacity, decline in organic matter and decline in biological activity in soil), removal of nutrients from the land without replacement (harvest events), erosion and runoff, and leaching of nutrients. Decline in soil chemical fertility results in increasing dependence on fertiliser inputs for agricultural productivity. Increased loss of sediments leads to movement of sediment bound nutrients in surface runoff and transportation through the soil environment, translocating nutrients to other

regions of a catchment resulting in a further decline in soil chemical fertility. Nitrogen and phosphorus moving as sediment bound particles often reach stream or river channels, which can result in eutrophication of aquatic ecosystems if nutrient levels exceed certain concentrations which increase the likelihood of potentially harmful algal blooms which cause an imbalance in fresh and marine ecosystems harming aquatic plants and animals. Algal blooms also affect water uses such as recreational activities, palatability of water, stocking and agriculture waters (Scholes *et al.*, 2007, FIFA, 2007).

Continual fertilizer application in agro-ecosystems often results in soil surface crusting which in turn leads to an increase in nutrient transport through overland flow pathways (e.g. runoff). Surface crusting or surface sealing in cultivated soils occurs as a result of aggregate breakdown with the ongoing practise of successive cycle of wetting and drying and frequent mechanical disturbances. Soil surface crusting restricts water and solute infiltration into soils and in some cases prevents infiltration completely (Mathers et al., 2007). However, the converse can occur with the saturation of the root zone after fertilizer application resulting in saturation-excess overland flow of nutrients and sediments. The process of surface crusting is more common in sodic soils, or other soil types with inherent structural stability issues. The hardsetting or crusting of soils results in reduced infiltration and increased surface runoff by processes of wind and water erosion. Residues such as those from eucalyptus species can leave hydrophobic residue on the soil, acting as a water/solute repellent layer, again resulting an increase in nutrient transport via surface pathways. Heavy vehicle use during farming practises or high stocking rates of cattle and sheep results in the compaction of soils, and hence, the alteration of physicochemical and structural properties of soils. This alteration of soil permeability from soil compaction leads to an increase in surface or overland flows as water infiltration (the downward entry of water into the soil, driven by gravity and capillary action) to the soils is significantly reduced.

Significant amounts of nitrogen and phosphorus fertilisers are applied annually across Victorian agricultural regions. Different levels and rates are applied for different farming purposes; however fertilisers prior to plant uptake are at risk of loss via processes of denitrification, ammonia volatilisation, losses in runoff from irrigation bays or rainfall, and leaching (DPI, 2005). Accurate and current data for the quantity and application rates for nitrogenous fertilizers has been difficult to obtain. Several avenues for obtaining such information were explored. Data found within the DPI website was interrogated, as was information from several fertilizer companies that supply farmers in Victoria. Majority of the available data was in reference to rates, fertilizer type and timing of application rather than data specific to quantity application. The Fertilizer Industry Federation of Australia found in 2005 an average load of ~1000 Kt of nitrogen and ~450 Kt of phosphorus was being applied Australia wide in fertilizer products, however current data for the 2005-2009 period was not available (FIFA, 2007). In 2008, the Victorian DPI recommended nitrogen application at sowing was no more than 12 kg/ha of actual nitrogen for pastures or crops, whilst the recommendation for phosphorus application at sowing as between 10-25 kg/ha of phosphorus (DPI, 2009). Given the absence of comprehensive data, it

is recommended that a study is undertaken to acquire accurate and detailed information on the application quantities of nitrogen and phosphorous fertilizers across the Victoria agricultural region.

2.3.2 Nitrogen

Nitrogen inputs to soil are derived from sources such as fertiliser additions, plant/crop residue breakdown, mineralization from soil organic mater, and pasture/legume nitrogen fixation (Newham & Drewry, 2006, Cameron *et al.*, 2002, Pakrou & Dillon, 2000, Balasubramanian *et al.*, 2004). There are four main loss pathways for nitrogen:

(1) Erosion and runoff of nitrogen;

(2) The leaching of nitrogen in the form of nitrates, but also as nitrites, ammonium, and soluble organic N;

(3) Ammonia volatilization; and

(4) Gaseous emission (NO_2 and N_2) from nitrification and denitrification processes.

Nitrogen losses are influenced by N inputs, crop selection and faming practises such as tillage and land drainage, factors which can be controlled to a certain level. However, factors such as climate and soil type that contribute to N loss are outside our control and significantly influence the rate and degree of which N loss is experienced from a landscape, and hence these rates vary by region (Goulding, 2004, Mosier *et al.*, 2004a).

Rather than direct losses of N from applied fertiliser, the leaching of N often occurs via high concentrations from cattle and sheep urine (Cameron et al., 2002). The nutrient load of a region will depend on the cumulative amounts of N fertiliser applied and the grazing intensity within the catchment (Eckard *et al.*, 2004). Nitrogen transport can be divided into surface (overland flows) and subsurface pathways (Newham & Drewry, 2006, Drewry *et al.*, 2006). Significant amounts of N in Australian catchments are lost to groundwater via large soil macropores or soil drainage pores (Rasiah *et al.*, 2003), tile and mole drainage systems (Eckard et al., 2004), under irrigation and grazing pastures (Newham & Drewry, 2006, Pakrou & Dillon, 2000).

2.3.3 Phosphorus

Phosphorus is an essential nutrient for crop production and animal production (cattle and dairy farming); however, P can accelerate the eutrophication of freshwater. Eutrophication of freshwater severely impairs water quality, restricting water use for fisheries, industry and recreation due to the increased levels of algae and aquatic weeds leading to reduced available oxygen in the water. Harmful algal blooms (e.g. *Cyanobacteria* and *Pfiesteria*) caused by P fuelled eutrophication leads to fish death and the unpalatability of drinking water to humans (Neitsch et al., 2005). Majority of phosphorus is lost or transported within a catchment via surface runoff. Phosphorus enters water bodies from both point and non-point sources. Non-point sources of P are agriculture (fertiliser inputs), intensive livestock agriculture (manure and fertiliser inputs), urban contributions such as fertiliser applications on laws, construction sites. Phosphorus is transported from source areas by surface runoff, erosion and subsurface flows.

The amount of P available to be transported via these pathways is influenced by the physical and biochemical characteristics of the soils, cropping and land management practices. Surface runoff, erosion and subsurface flows mobilise P sources, creating pathways of P loss from a catchment or specific regions within the catchment (Chaubey *et al.*, 2006, McKenzie et al., 2004).

In general, majority of P loss occurs via surface runoff. The main controlling factors of P transport and loss, particularly in agricultural catchment regions, are erosion and surface runoff. Potential P loss via erosion is the transport mechanism that preferentially removes finer-sized particles as sediment or soil transport across the soil surface to surface water bodies. The amount of P delivered to surface water bodies is influenced by the flow, distance and connectivity of the source site to the stream or channels. Surface runoff from a site can cause significantly high P loss. When the saturation of surface soils occurs (rainfall interacting with the thin top layer of soil) dissolved P is transported in surface runoff as P is released from the soil, suspended sediments or plant material. Inevitably rainfall intensity, soil tilth and vegetative cover dramatically influence surface runoff potential, with the variation of these factors across a landscape determining the P loss potential via surface runoff pathways. Subsurface loss of P by leaching is the percolation of mobilized P in water. In most cases, leaching of P is infrequent due to sorption of P by P-deficient subsoils. However, in soils where capacity for P sorption is low such as organic soils, soils that are water-logged or have a high permeability (e.g. sandy soils), well structured soils prone to flows through earthworm burrows or soil macropores. If leaching of P occurs, lost P can enter groundwater via percolation and is then re-released into surface waters by lateral interlayer soil flows or is retained in soils (Sharpley *et al.*, 2001, Peverill *et al.*, 1999, Drewry et al., 2006, McKenzie et al., 2004).

Loss of dissolved P is dependent on the surface soil P concentrations. Phosphorus exported from agricultural landscapes comes mainly from small regions, occurring after a large storm event where the hydrological activity contributes to the surface runoff to surrounding water bodies. However, landscapes differ in their susceptibility and P loss potential via surface runoff due to distinct topographies and management practices. Land management factors such as fertiliser application rate, time and application methodology influence P loss. Time from P additions to soil and time between addition and rainfall events significantly affect to amount of P lost. Phosphorus transported in overland surface runoff is also affected by the degree of vegetative cover over the soil, as it acts as an intercept to rainfall intensity and stabilises soils (Drewry et al., 2006, McKenzie et al., 2004). It has been estimated that approximately 10% of P applied in an agricultural system is lost in runoff, unless heavy rainfall follows soon after P application.

2.3.4 Review of tree removal impacts on nutrient dynamics

Clearing of vegetation within a catchment can have serious impacts such as increased salinity and increased runoff to neighbouring waterways containing higher sediment, nutrient and even toxic chemical loads. Many land degradation problems in Victoria have resulted from the extensive clearing of native vegetation, resulting in highly visible soil erosion (both wind and

water) often taking the form of gullies and landslides. Land clearing negatively impacts soil health due to higher surface runoff rates caused by soil destabilization from the removal of vegetative cover results in nutrient losses. Heavy machinery used during the tree removal process can compact soils up to 90% resulting in reduced root penetration, aeration and infiltration capacity, in turn leading to soils that are highly erosive, prone to saturation and that reduce/inhibit seedling growth (Martin, 1988). Soil disturbance caused during the tree removal process leads to large losses in nutrients and soil structure degradation (Pierce *et al.*, 993). The of the destabilization of soil, and the mobilization of sediments and leaching of nutrients during and post tree removal impact broadly across a catchment, resulting in deposition of sediment and nutrient loads into catchment tributaries and water channels (Hornbeck *et al.*, 1990). Riparian vegetation plays an extremely important role acting as a interface between land and waterways by filtering sediments, nutrients, chemicals, and other wastes from contaminated surface runoff, and by protecting stream bed and bank stability to minimise erosion contributions to water sediment and nutrient loads (EPA, 2009). Riparian vegetation zones are a critical final point of nutrient interception and buffering between surface runoff and mobile sediment bound nutrients, and waterways. Current research clearly indicates that these vegetation buffers play an important management role in reducing nutrient loads entering streams and rivers from surrounding agricultural landscapes via both surface and sub-surface pathways (Mayer *et al.*, 2006). As such, riparian zones are a key management point for point and non-point source pollutants and nutrients flowing between the terrestrial and aquatic environments. There appears to be a knowledge gap in the current scientific literature regarding best management practice for the use of riparian zones in managing nutrient deposition into waterways from upland sources of nutrients into aquatic systems, particularly in Victoria (e.g. fertilizers, animal wastes, and surface runoff). This highlights the need for further studies to be undertaken to better determine the role that riparian vegetation plays in nutrient impact mitigation and advance our understanding of the movement of nutrients between the aquatic and terrestrial environments within the context of nutrient cycling.

Total tree removal has significant impacts on the soil environment and can dramatically alter the dynamics of terrestrial nutrient cycling. The impact of tree removal is two fold. Logging residue can significantly affect export and dynamics of nutrients, whilst the tree removal has several different negative implications for soil health and the export and dynamics of nutrients. Total tree removal has substantial effects on the soil environment, impacting soil moisture and temperature conditions as a result of increased radiation reaching the soil. In turn, this significantly alters the soil microbial activity which influences the rate of organic matter decomposition and nutrient turnover (Ouro *et al.*, 2001). Post total tree removal sees an increase in nutrient ions in streams and soil solution occurs, and is attributed to the increased mineralization that occurs immediately after harvest (Hornbeck & Kropelin, 1982). The clear-cutting of forest has been identified as a major cause of nutrient loss, stream acidification and the mobilization of potentially toxic nutrients (e.g. Al species) into waterways contributing additional stress to aquatic environments and ecosystem function (Dahlgren & Driscoll, 1994,

Likens *et al.*, 1970). Thus far, no studies that directly address the impacts of total tree removal on catchment nutrient dynamics have been identified in Australian literature. Our current understanding of the long-term impacts and implications of clear-felling in Victorian catchments are far from complete (Kuczera, 1987). Studies abroad have shown that whole tree removal and land cover change significantly alters the hydrological behavior and nutrient dynamics of a landscape (e.g. Yanai, 1991, Yanai, 1998, Fahey *et al.*, 2005, Likens et al., 1970).

The classic experimental study that has been undertaken to determine the impacts of whole-tree removal on soil processes and stream chemistry is from the Hubbard Brooke Experimental Forest (HBEF) situated in the United States of America, New Hampshire (Likens *et al.*, 1970, Dahlgren & Driscoll, 1994) Although the climate and elevations from this study location are not directly comparable to those found within Victoria, the results are indicative of the impacts of tree removal on nutrient transport mechanism within a catchment. Dalhgren and Driscoll (1994) found that at HBEF whole-tree clear-cutting creates significant ecosystem disturbances, leading to a significant loss of nutrients from the soil profile and increased soil acidification. The results from this study indicate that streams that are heavily impacted by clear-cutting in the catchment, demonstrating that drainage water chemistry is significantly altered following tree harvest. Clear-cutting was found to eliminate the vegetative sink for many nutrients (N, P, K), resulting in leaching loss as mineralization processes proceed, whilst non-essential plant nutrients showed no significant response to clear-cutting. The major source of nutrient loss was found to be derived from the organic or humus layers (forest floor) and upper soil horizons due to the lack of nutrient uptake by plants caused by vegetation removal. Notable changes in the soil chemistry were the large increase in NO_3-ion concentration throughout the soil profile, reaching a maximum one year post-harvest, leaching of basic nutrients such as Ca-ions, Mg-ions and K-ions was observed, whilst inorganic forms of P experienced little redistribution and Na-ions increased in leachates. The most profound observed differences in soil and stream chemistry were observed on year post-harvest, demonstrating a certain period of lag effects of released solutes to the soil solution and stream waters. Dalhgren and Driscoll (1994) explain the lag period as a result of decomposition of organic pools on the forest floor and the microbial productivity reaching a maximum in the upper soil layers prior to extensive leaching. Interestingly, in the HBEF study, the loss of nitrogen from the soil profile occurred only as NO_3-ion. This was attributed to nitrate being highly mobile and the removal of vegetation removes the only pathway by which nitrate can be immobilized as uptake and incorporation into plant tissues, resulting in an unhindered leaching of NO_3-ion. It is evident that significant changes in soil solution and water chemistry occur after tree removal in a catchment, with the affects reaching further than the immediately altered area. The results from the studies at HBEF clearly indicate that whole-tree removal significantly alters the nutrient and hydrological dynamics of a catchment, leading to a significant loss of nutrients from the soil profile via leaching, loss in mobilized sediments and increased soil acidification. Streams are heavily impacted by clear-cutting in a catchment, with water chemistry displaying significant alteration post-harvest. The magnitude of these findings highlights the need for extensive research into the impacts of whole-tree removal within

Australian catchments, to determine if the results from previous studies correlate with the dynamics in Australian catchments, and lead to the creation of effective management practices.

2.3.5 Nutrient modelling for catchment management

Catchment modelling frameworks provide catchment managers with tools to integrate complex biophysical processes to predict potential catchment responses to land use change, nutrient load additions or removals, and altered nutrient and sediment cycles (Beverly *et al.*, 2005). Several models are available for simulating the biogeochemistry of an entire catchment (e.g SWAT). These models are usually inclusive of hydrological models, drawing focus to nutrient transport and export to waterways (e.g. LASCAM/CatchMODS) and include vegetation models focused on yield/growth of agriculture, forests, and other vegetation categories (e.g. DAYCENT). Several models account for the nitrogen and carbon dynamics in examining ecosystem nutrient impacts; however, the increasing body of literature on the importance of phosphorus impacting aquatic systems suggests that models must either be adapted or different models used by Catchment Management Authorities (CMA) for increasing accuracy in analysis of nutrient and sediment transport. Depending on the aims of the modelling exercise, the level of detail needed to accurately represent the movement of nutrients in an ecosystem must be considered at an appropriate resolution. The degree of complexity in available models varies greatly in the representation of chemical and physical processes occurring in the catchment (Sangjun *et al.*, 2007). To best understand processes occurring at a whole-catchment scale, a model must be able to incorporate nutrient export and cycling, as well as climate and hydrology models, and vegetation dynamics models (growth/yield). Very few models are able to incorporate all these modelling facets, and there is often a trade-off between a model's complexity and its predictive powers. An understanding of nutrient cycling in terrestrial ecosystems, especially soil, is particularly well developed, yet different models place an emphasis on different components of this cycling, and represent these processes as various temporal and spatial scales. A comprehensive understanding of transport and export of nutrients in a catchment, particularly sediments, nitrogen and phosphorus in terrestrial ecosystems is essential for understanding the resulting impacts on water quality and stream/river health.

There is a plethora of different models available for modelling nutrient export and transport for catchment management; however, each with limitations and constraints. Models differ significantly in the emphasis placed on cycles occurring in a terrestrial ecosystem, and on the degree of detailed empirical input data required to represent these processes. Some models are more complex, requiring significant parameterization and calibration, whilst other empirical models are simpler and can produce more accurate results. The complexity of an empirical model can be both advantageous and disadvantageous depending on the information output desired from the given modelling exercise. Many models currently used in Australian catchment management were developed in countries with very different key processes of erosion and sediment transport than those in Australia. These models often have large data input requirements of detail that is often unavailable in the majority of Australian catchments. Again

the issue of scale is encountered, with most Australian studies occurring at plot or first order catchment resolution, with little detailed knowledge of the entire catchment nutrient inputs, loadings and transport. In many cases information is limited and the available data is insufficient or inappropriate, rendering the model inaccurate or unable to sufficiently account for catchment processes (Letcher *et al.*, 2002). A comparative study by Letcher *et al*. (2002) reported that over- or under-estimation of nutrient and sediments loads within a catchment system are highly dependent on the model selected for analysis when limited or sparse data is available. The large variability in results found from this study has serious implications for researchers and CMAs and managers when attempting to estimate nutrient and sediment loads in catchments where data is sparse. Therefore, when available data is sparse, model choice must take into consideration several important points: the useability of the model; key processes represented and modelled; and the broader objectives of the modelling or estimation exercise.

Catchment managers are faced with several challenges such as limited tools and finite resources to develop tools that are cost effective and target best strategies to maximise impact of catchment health (Beverly *et al.*, 2005). There appears to be a need for greater coordination between different agencies and authorities responsible for data collection. This will increase accessibility to a variety of useful resources and assist in accurate and complete environmental assessments and understandings of pollutant loads and movements within catchments. No central database appears to be kept and maintained, and as a result in many cases obtaining data (past and present) was challenging or in some cases not possible for the purpose of this report. Climate data (rainfall and temperature) is often limited to availability from meteorological stations, and is hence biased by the location of stations which are often found in urban regions or forestry areas (Letcher et al., 2002). Length of monitoring projects and testing site locations will also influence the accuracy the data. The study by Letcher *et al.* (2002) emphasises the need for governing bodies and authorities to work collaboratively to create a centralised database accessible for modelling and management purposes to bridge the data gap between those who collected it and those who will use it for research and management purposes.

Detailed and complex models have predictive capacities and are able to assess within-catchment dynamics at a range of scales, and can account for complex surface/groundwater interactions and differing landscapes (Beverly et al., 2005). Scale (spatial and temporal) plays an extremely important role in determining the extent and detail of input data and model complexity required for a particular outcome or modelling goal (Weeks *et al.*, 2008). It is important for policy makers and CMAs to consider both the costs and benefits of different outcome relative to the social, economic and environmental values of different assets and stakeholders. Balancing the required economic, social and environmental outcomes poses a significant challenge to CMAs in the agricultural and natural resource context. Favouring environmental health over economics leads to a reduced capacity of a landscape to provide financial prosperity to a region, whilst focussing on economics alone will lead to a degraded environment. Taking all aspects (economic, social and environmental) into account, landscape management frameworks and modelling systems

need to reflect the interconnected nature of natural landscapes, managed landscapes and the services provided by the landscape to a variety of stakeholders. The importance of integrated and linked models cannot be emphasised enough. Biophysical models used for catchment management, modelling and simulation must take a holistic and integrated approach to understanding and evaluating landscape processes and future implications of landscape management. Linkages between models reflect the natural interconnectedness of landscapes and landscape processes, allowing for querying the affects of one process on another (Weeks et al., 2008).

While this report focuses primarily on SWAT, we provide (Section2.6) a comparison of models. While no single model will be ideal for all situations, we consider the following elements important to be held within the model framework:

- Nitrogen
- Phosphorus
- Carbon
- Water balance
- Daily step
- Erosion
- Management inputs
- Vegetation/plant growth
- Climate/weather
- We also put significant weight on:
- Peer review
- Validation
- Open access to model component (i.e. can see inside)

2.4 Nutrient (N & P) requirements of plants

The forms and quantities of nitrogen and phosphorus required by plants vary with land use and management (Drewry *et al.*, 2006). The nitrogen and phosphorus requirements of a plant change between species and among different stages of development. Critical nutrient concentration, which is just adequate for maximum growth (Ulrich, 1952), is the standard concentration used for diagnosing nutrient deficiency or toxicity in plants (Figure 1). The nutrient status of a plant influences the rate of development, extent of growth by limiting the photosynthetic capacity, productivity and yield, and can even alter morphological features (Epstein & Bloom, 2005). The internal concentration of nutrients in different plant tissues is generally restricted to a narrow range, regardless of the available nutrients in the surrounding environment, demonstrating a plants unique ability to fine tune the amount of nutrients absorbed. Internal tissue nutrient concentrations are different for the various plant tissues with some tissues such as seed tissues being restricted to narrower limits than root and shoot plant tissue. For different nutrients, the patterns of distribution (partitioning and remobilization) and rate of uptake and cycling within the plant tissue varies greatly, effected by nutrient availability, plant nutrient status, stage of development, environmental conditions such as soil pH and plant species (Reuter *et al.*, 1997, Epstein & Bloom, 2005).

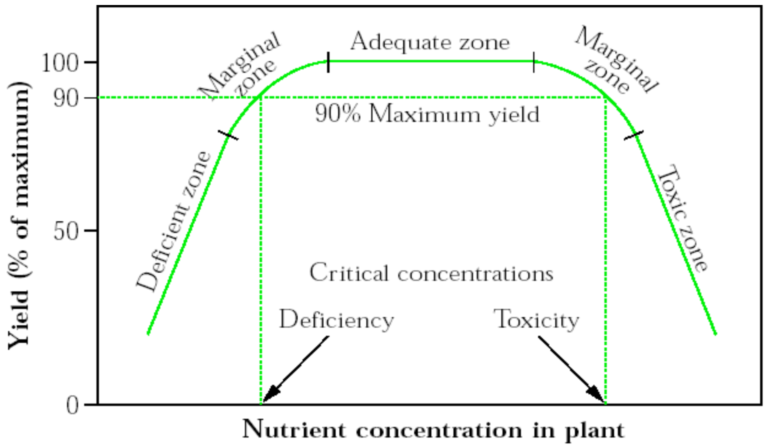

Figure 5. Generalised plot of plant growth in response to changes in nutrient concentrations, and critical concentrations for diagnosing toxicity and deficiency in plants (source Reuter et al., 1997 p.11). Formal permission not sought.

The partitioning and mobilization of nutrients within plant tissue is again different for perennial and annual plants, as nutrient concentrations of different plant tissues are tightly linked to phenological stages of development. If the nutrients absorbed by a plant are in excess of requirement, it may be stored, excreted, abscised with plant tissue or result in plant death. Nutrients deposited in plant tissue and organs can however be remobilized and translocated during plant development or during nutrient stress leading to a rapid redistribution of nutrient

concentrations within the plant. All nutrients move in the xylem, however not all nutrients move within the phloem. Both nitrogen and phosphorus however do have phloem mobility enabling them to cycle rapidly throughout the plant (Reuter et al., 1997). When examining plant tissue nutrient concentrations, traditionally they are examined in the following categories: roots, shoots, stems and leaf. However, there are several approaches for plant tissue nutrient concentration analysis. Nitrogen and phosphorus concentrations and ratios for different plants will vary under different conditions depending on soil, genotype, and other environmental factors. Generalised adequate overall concentrations of both N and P macronutrients in plant tissue (concentration in plant dry matter) have been determined as 1000 µ mol g^{-1} (1.5 %) and 60 µ mol g^{-1} (0.2 %) respectively. If essential nutrients such as N and P in plant tissues drop below a level required for optimal, the plant is considered deficient in that element (Epstein & Bloom, 2005).

Reuter et al. (1997) explicitly state that a single definition of the critical nutrient concentration of a plant or plant tissue is insufficient, rather that the evidence in the literature and the empirical approach to plant analysis that has emerged, suggests that the use of a critical nutrient concentration range is more appropriate. Determining plant nutrient concentrations plays an important role in correcting existing nutrient problems or preventing their occurrence in the future. Understanding the available nutrient stores within the plant, supply from soil and the plant requirements for growth and yield are also extremely important, as is the ability to determine appropriate fertiliser application of certain nutrients to prevent pollution (Reuter et al., 1997). Nutrient supply to plants is influenced by soil physical and chemical characteristics; where as nutrient uptake by plants is affected by plant genome, mycorrhizas, soil temperature, water, and soil pH (Epstein & Bloom, 2005). Significant differences are widely apparent in plant species ability to obtain nutrients from the soil (Reuter et al., 1997), and as a result can lead to different fertiliser requirements and recommendations.

Nutrient deficiency and toxicity in plants cause impaired metabolism resulting in visible symptomatic expression in plant appearance. Symptoms such as impaired metabolism or reduced growth are characteristic to the nutrient deficiency or toxicity of the plant, and expression can vary among plant species. However, other symptoms are less characteristic, and the presence of these symptoms can suggests a variety of possible stresses. Cereal crop species such as *Triticum sp.* (wheat) and *Hordeum sp.* (barley) commonly display N deficiencies as chlorosis of the whole plant, leaf necrosis, retarded or stunted growth, restricted tiller development, altered colour of leaves and leaf veins, often the reddening of leaves, with mature foliage affected first. Crop species suffering P deficiency have dark green foliage, often displaying reddening or purpling of leaves or petioles, with mature leaves affected first (Elliott et al., 1997b, Reuter et al., 1997). In general N and P deficiency in pines or eucalypts is expressed by paleness of shoots with reddening/purpling and premature senescence of old leaves (Judd *et al.*, 1996). Nitrogen deficiency in pines is also displayed by the fine branching of the central trunk (Reuter et al., 1997). *Eucalyptus globulus* is defined as a symphyomyrtus eucalypt species, those which are found on sites of higher nutrient concentrations, and species falling within this subgenera

category are more responsive to nutrient additions expressed as increased growth (Noble, 1989, Judd et al., 1996). Grasses and shrubs play an important role in nutrient uptake in natural landscapes, especially in riparian regions. This report has not drawn focus to either of these vegetation types, yet it seems that determining their nutrient requirements and nutrient concentrations in various plant tissues would be extremely valuable, given the role that both these vegetation types can play in riparian restoration, and nutrient management between agricultural zones and waterways. Although less well studied, grass-shrub vegetation buffers have been identified as means of efficient in removal of sediments, N, and P to reduce nutrient and sediment loads entering waterways adjacent to agricultural zones (Mankin *et al.*, 2007). Future research should include a determination of typical grass and shrub plant tissue nutrient requirements and concentrations to better assist in restoration initiatives and catchment management practises. Nutrient concentrations in foliage are particularly useful and important for the identification of nutritional deficiency, stress, and or imbalances as foliage is particularly sensitive and responsive to nutrient changes, site fertility and fertiliser additions (Judd *et al.*, 1996). Correctly assessing the nutrient status of plant tissue is very important for diagnosis of nutrient deficiencies or toxicities, and developing appropriate land management practises. Many visual symptoms can be used to identify nutrient deficiencies in crop and plantation species (as well as natural forests), however as a sole diagnostic tool, visual symptoms can fall short of accurate and timely diagnosis and remediation. Consequently, it is important to have an established understanding of average of accepted plant tissue nutrient concentrations to base assessments upon. The following sections 2.4.1 and 2.4.2 provide nutrient concentrations for plant tissues listed in tables reported on an oven-dry basis as percentages (%). The nutrient concentrations listed in tables are accompanied by growth or developmental stages of phenological development (e.g. tillering, mature grain) or plant age (e.g. 36 days from sowing). Phenological development stages have been classified using either the Zadok's scale for growth stage, or for some crops defined using growth stages defined by Large et al. (1974). Forest species are grouped into three categories of seedling, juvenile or mature. Nutrient concentration values in each table are divided into the following categories: marginal, adequate, critical. Marginal nutrient concentrations refer to tissue concentrations of plant tissue falling within the marginal zone (see Figure 7.) that do not contain enough of a particular nutrient to reach a 90% maximum yield, but are not severely deficient in nutrients. Adequate refers to nutrient concentrations in plant tissue that enable a 90% maximum yield in produce or plant material. Critical concentration refers to nutrient concentrations that are approaching either nutrient deficiency or toxicity in plant tissues (Reuter et al., 1997).

2.4.1 Plant nitrogen requirements

Plants require a greater amount of nitrogen than any other nutrient. The availability of nitrogen limits plant growth and productivity in both natural and agricultural environments. The nitrogen content of leaf tissue is directly linked to the photosynthetic capability of a plant. The photosynthetic capacity exponentially increases with leaf nitrogen increase (Epstein & Bloom,

2005), however efficiency declines when concentrations exceed assimilation capabilities. Nitrogen fixation is the process by which atmospheric nitrogen is made accessible for uptake by plants. This process occurs via several pathways such as bacterial, atmospheric, biological or industrial fixation of nitrogen into nitrates and ammonium. Decomposition of soil organic matter also releases nitrogen available to plant acquisition. Crop plants allocate a significantly larger amount of nitrogen to seeds than other plant tissues. Nitrogen concentrations of crop plants can range from 0.5-6 % of the plant material (dry-weight basis), whereas grains of crop plants (cereals) contain between 1.6 % and 3.0 % nitrogen (g N/g dry weight of grain). Nitrogen deficiency in plants is commonly exhibited as retarded and slow growth, and plants display a spindly and discoloured appearance. The more mature plant tissues are first affected by nitrogen deficiency as nitrogen is translocated within the plant from older to younger growth regions (Epstein & Bloom, 2005).

Wheat: *Triticum durum* and *Triticum aestivum* L

Nitrogen fertiliser application is widely used in Australian wheat production as the biological and economic benefits have been clearly demonstrated. However, there is wide variation in both soil type (and associated N levels) and N-fertiliser application across the wheat growing regions of Australia. As such, knowing optimum application rates and concentrations of N-fertilisers to achieve maximum grain yield have become increasingly important. The requirements, uptake and storage of nutrients in *Triticum aestivum* L. change with plant developmental stages, however these requirements are not significantly different between wheat genotypes commonly grown in Australia (Elliott *et al.*, 1997a). Nitrogen is a primary constituent of grain protein. Only when sufficient nitrogen is available for uptake by wheat is the crop able to produce a grain with a high percentage of protein, making soil fertility essential for producing high quality wheat (Brennan & Bolland, 2009). To ensure adequate nitrogen fertiliser application to maximise grain yield without diluting the effect on grain protein levels, it is important to understand adequate and critical nitrogen concentrations of wheat plant tissues. Critical total N concentrations of wheat vary widely among the various plant tissues (leaf blades, shoots, sheaths, stems, grains and roots), and are greatly affected variably by plant age and N supply (Strong & Mason, 1999). For wheat under N-adequate conditions, N concentrations markedly and progressively decrease with advancing physiological plant age of the particular plant tissue (see Table 1). As with many other cereal crop species, nitrogen stress is expressed by *Triticum durum* and *Triticum aestivum* in the mature leaves initially, but often chlorosis of the whole plant occurs as the limited nitrogen is transferred from the mature foliage to new growth regions. Often this is accompanied by reddening in colder climates (Reuter et al., 1997). Phenological development stages have been classified using either the Zadok's scale for growth stage, or for some crops defined using growth stages (Feeke's scale) defined by Large et al. (1974).

Plant Tissue	**Growth Stage**	**Growth Category**	**Critical Deficiency (% dry weight)**	**Adequate (% dry weight)**
Whole Shoot	FS2	Early tillering	6.66	-
(N% in WS relative to	FS3	Tillering	5.39	-
grain yield, predictive)	FS4	Tillering	5.45	-
	FS5	Tillering	5.15	-
	FS6	Stem extension	3.08	-
	FS7	Second node visible	3.12	-
	FS9	ligules of last leaf visible	2.44	-
	FS10	In 'boot'	1.37	-
	FS10.5	Heading	1.69	-
	FS11	Ripening	1.47	-
	Mature	Mature	1.28	-
	Late Till	Late till	>4.0	-
YMB	Mid to late Till	Mid to late till	-	3.5-5.4
	36 DAS	Seedling	4.5	-
YEB	2-3 leaf	Seedling	-	4.0-6.5
Leaves	FS1.5	Seedling	5.35	-
	FS5	Tillering	4.75	-
Young Leaves	FS10.3	Heading	4.25	-
Basal Stem	FS1.5	Seedling	3.04	-
	FS5	Seedling/tillering	2.8	-
	FS10.3	Heading	2.2	-
Grain	Mature	Mature	2.0-2.3	>2.0
Roots	-	-	-	-

Table 1. Estimated total N concentrations (%) of wheat (*Triticum durum* and *Triticum aestivum*) tissues at different developmental stages of plant ontogeny. Data taken from Reuter *et al.* (1997). Youngest emerged blade (YEB), young mature leaves (YMB). Growth stages define using Feeke's scale (FS) of growth stages in cereals, Zadok's decimal code for the growth stages of cereals and days after sowing (DAS)

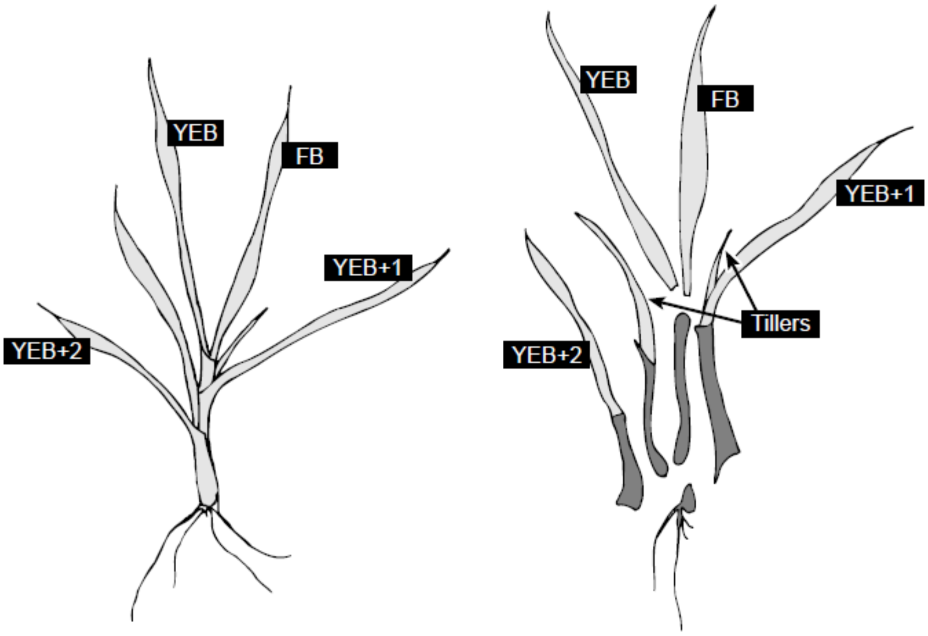

Figure 6. Diagrams of an intact and dissected wheat plants, showing the individual position of leaf blades. Folded blades (FB), youngest emerged blade (YEB), and successively older blades (YEB+1, YEB+2), tillers or new growth (NG). Source Elliott *et al.* (1997c) p.871.

Barley: *Hordeum vulgare*

Nitrogen is essential for early tiller development of barley, and to establish the crop for a high yield potential. Nitrogen is also an important part of proteins, and the availability of this nutrient to the barley crop largely determines the protein concentration in the resulting grain produced. Nitrogen is taken up by plants when it is in an inorganic form (ammonium or nitrate). The nitrogen required to grow a successful barley crop must be supplied from the soil or as fertiliser. The amount of nitrogen required for a successful crop differs between genotypes, however to maximize yield and quality of barley crops will depend on the seasonal conditions, soil type and rotational history of the paddock, as well as the potential yield of the crop. It has been estimated that 40 and 54 kg of mineral nitrogen is needed in the soil for each tonne of barley grain produced (Bowden, 2007). Nitrogen deficiency symptoms are initially seen mature leaves, displayed by leaves turning a pale green and the leaf tip a pale yellow. The yellow discolouration of the leaf progresses down towards the leaf base, eventually turning a pale brown. The youngest leaves of the barley plant usually remain green (Bowden, 2007).

Plant Tissue	Growth Stage	Growth Category	Critical Deficiency (% dry weight)	Adequate (% dry weight)
Whole Shoot	FI	flowering	1.58	-
Roots	-		-	-
Grain	-		-	-
Basal stem	-		-	-
YMB (youngest mature leaf blade)	Mid to late Till		-	3.5-5.4

Table 2. Nitrogen concentrations (%) of plant tissues for *Hordeum vulgare.* Data taken from Reuter *et al.* (1997)

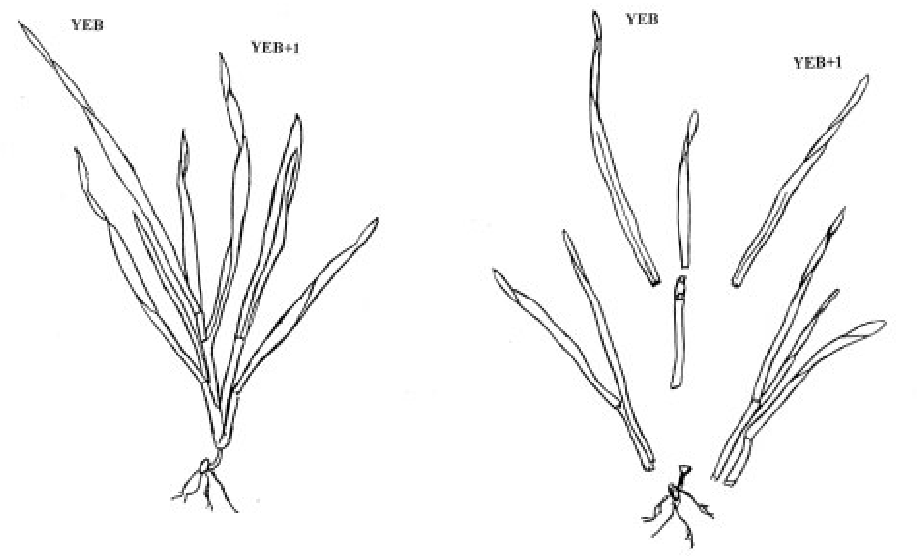

Figure 7. Diagrams of an intact and dissected barley plants, showing the individual position of leaf blades. Youngest emerged blade (YEB), and older blade (YEB+1). Source Hoppo *et al.* (1999) p.859.

Pastures:

Pastures are commonly used in crop rotation sequences, assisting farmers in maintaining soil stability and soil fertility (sustainable farming such as cover cropping techniques), control weeds, prevent soil erosion and diversify produce (Tow & Schultz, 1991). Pasture selection and suitable cultivars depends heavily on the management and market outcomes required. Crop rotation systems have been developed to assist with changing and developing ecological, economic and technological situations. Cover cropping is often used in Australian dryland farming to assist in the reduction of soil erosion, with pasture species acting as a protective cover, a soil stabiliser, and as a means of increasing soil nitrogen concentrations and availability for future crops. Pastures are often used to assist in increasing soil fertility through N-fixation as a means of

increasing long-term sustainability of the soil and increasing overall productivity, flexibility and stability. Selecting a pasture type appropriate for the farming and management objectives is important, and is influenced by regional climates (total rainfall and annual temperature variations) and soil type (surface and sub-surface pH, organic matter, nitrogen content, texture, structure, erodibility, and drainage and water holding capacity) (Tow & Schultz, 1991). The amount of N-fixation that a pasture crop can provide is an important consideration given it will influence the rate at which soil nitrogen concentrations are increased for subsequent crops (Dear *et al.*, 1999). Australian experimental studies have found that subterranean clover based ley farming systems can fix N_2 at amounts ranging from 5 to 240 kg N/ha (Peoples *et al.*, 1997) with a mean value of 92 kg N/ha (Unkovich *et al.*, 1997). The reported N concentrations in foliar tissue may significantly under-represent the amount of N per plant, as it has been reported that the below ground component of N-fixing plants can contain approximately 40% of the total plant nitrogen in their roots (Riffkin *et al.*, 1999a). South-western Victoria, situated in the temperate high rainfall zone, produces 28% of Victoria's milk supply, overall 17% of Australia's milk supply. Victoria's dairy region mainly relies on rain-fed pastures of *Trifolium repens* and *Lolium perenne* (Riffkin *et al.*, 1999b). N fixation under dairy farming is influenced by several biological, physical and chemical factors including plant nutrition, grazing management, pasture legume content, fertilizer and pesticide application etc. (Unkovich et al., 1997, Riffkin et al., 1999b). *Phalaris aquatic* is highly regarded as a pasture production species for livestock (Watson *et al.*, 2000), and is the second most widely sown perennial grass species in Victoria after perennial rye grass (*Lolium perenne*) (Reed, 1999). *P. aquatic* is commonly sown with other pasture species such as clover (*Trifolium* spp.) (Lamp *et al.*, 2001). *P. aquatic* is considered a high value pasture species and is commonly as it displays high productivity, ability to withstand drought, low susceptibility to disease, acts to exclude weeds, and has the potential to mitigate soil acidification and dryland salinity (Lamp et al., 2001, Watson et al., 2000, White *et al.*, 2000) Nitrogen deficiency is expressed commonly by pasture species on older leaves of the whole plant, displaying light green foliage and stunted growth. Cotyledons and unifoliates display yellowing, older leaves appear cupped, and reddening on the underside of the leaf and petioles can be observed (Reuter et al., 1997).

Species	**Young Tissue (N % dry weight)**	**Whole Shoots (N % dry weight)**
Trifolium repens (White Clover)	4.4-4.7	3.2-3.6
Trifolium Subteraneum (Subterranean Clover)	3.0-3.2	2.46-4.48
Phalaris aquatica (Phalaris grass sp.)	2.0-3.2	1.54-2.4
	-	2.4-4.53
Lolium perenne (Perennial Rye Grass)	3.0-3.5	2.0-3.2

Table 3. For *Phalaris* and *Lolium,* Young tissue: Young leaf blades collected when plants growing actively; Whole Shoots: Complete tillers collected when plant growing actively. For *Trifolium* sp. Young Tissue: Youngest open leaves collected during active growth, prior to flowering, Whole Shoot: Complete above ground growth collected prior to flowering. Data taken from Reuter *et al. (*1997) and Dear *et al*. (1999). Data expressed as % dry weight.

a b c d

Figure 8. a) *Trifolium repens* (White Clover); b) *Trifolium Subteraneum* (Subterranean Clover); c) *Phalaris aquatica* (Phalaris grass sp.); d) *Lolium perenne* (Perennial Rye Grass).

Generalized tree (seedling, juvenile, mature): *Pinus radiata* and *Eucalyptus globulus*

Mature tree crops derive majority of their N requirements from litter and leaf-fall (Strong & Mason, 1999), whilst crop residue returns provide a large proportion of the nitrogen requirements of subsequent plantation tree crops (McKenzie *et al.*, 2004). *Pinus radiata* and *Eucalyptus globulus* are two species common to Victoria, both are used as plantation species, whilst *Eucalyptus globulus* can be found growing in natural forests. These two species were selected as ‘generalized trees’ for use in this report as they provide a good representation for Victorian nitrogen requirements of a tree. Nitrogen deficiency in *Eucalyptus globulus* leads to leaf chlorosis due the reduced chlorophyll formation. In nitrogen deficient environments, mature or older leaves display yellowing as nitrogen is translocated from older leaves to new growth regions, however initial signs of nitrogen deficiency is expressed as mature leaves turning a pale green leaving the major leaf veins broadly and irregularly flanked with green. In *E. globulus*, leaf surface waxes mask the early stages of chlorosis, however with time yellowing of mature leaves will also spread to new growth, and leaves become uniformly yellow (Dell *et al.*, 2001). Nitrogen deficiency in *Pinus radiata* can be observed by the overall yellowing and pale green appearance of pine needles over the whole tree. The tree is often slender with a thin crown and fine branches (Reuter et al., 1997).

Species	Growth Stage	Plant Part	Marginal (N % dry weight)	Adequate (N % dry weight)
Eucalyptus globulus	Seedling	YMF	1.7-2.0	2.0-2.8
(Tasmanian Blue Gum)	Juvenile	YMF	1.7-2.1	2.0-2.9
	Mature	YMF	-	<1.2-1.9>
	Mature	New Leaf	-	0.867
	Mature	Twig <2 cm diameter	-	0.302
	Mature	Leaf litter	-	0.63±0.07
	Mean	Foliar	-	1.21±0.04
Pinus radiata	Seedling	YMF	1.0-1.2	1.6-2.4
(Plantation Pine sp.)	Juvenile	-	-	-
	Mature	YMF	1.0-1.2	1.2-2.0

Table 4. YMF: Young Mature Leaf. All concentrations for *Eucalyptus globulus* are for irrigated plantations. Data taken from Judd *et al.* (1996)

Stand of trees (seedling, juvenile, mature): *Pinus radiata* and *Eucalyptus globulus*

At present, information for of the nitrogen requirements of a stand of trees has not been identified. It is recommended that research is undertaken to close the gap on forest dynamics concerning nutrient content of a typical stand of trees in an Australian landscape. This must be accompanied by a definition of a typical stand of trees, incorporating stand age, average tree diameter at breast height (DBH) and tree height. **2.4.2 Plant phosphorus requirements**

Phosphorus is an essential nutrient required by plants for photosynthesis, playing a key role in the acquisition of energy, storage and utilization of metabolites. As with many other mineral nutrients, plants allocate a greater amount of phosphorus to grains than other plant tissues. In crop plants, phosphorus concentrations can range from 0.15-0.5 % of the plant material (dry-weight basis). Grain phosphorus concentrations range from 0.2-0.5% (g P/g dry weight of grain), whereas mature leaves will contain approximately half (or less) of this concentration. Phosphorus deficiency in plants is commonly exhibited as dark green or blue-green foliage, often red, brown and purple pigments develop on leaves and leaf veins. Plant growth is reduced and under severe phosphorus deficiency plant growth is stunted (Epstein & Bloom, 2005). Australian soils are typically low in available P.

Wheat: *Triticum durum* and *Triticum aestivum* L.

Phosphatic fertiliser application is widely used in Australian wheat production as the biological and economic benefits have been clearly demonstrated. However, there is wide variation in both soil type (and associated P levels) and P-fertiliser application across the wheat growing regions of Australia. As such, knowing optimum application rates and concentrations of P-fertilisers to achieve maximum grain yield have become increasingly important. The requirements, uptake and storage of P in *Triticum durum* and *Triticum aestivum* L. change with plant developmental stages, however these requirements are not significantly different between wheat genotypes

commonly grown in Australia (Elliott *et al.*, 1997a). Critical total P concentrations of wheat vary widely among the various plant tissues (leaf blades, shoots, sheaths, stems, grains and roots), and are greatly affected variably by plant age and P supply (Elliott et al., 1997c). For wheat under P-adequate conditions (defined by Elliot *et al.*, 1997 as 27 mg P/kg soil) total and labile P concentrations markedly and progressively decrease with advancing physiological plant age of the particular plant tissue (Elliott et al., 1997c). P-stressed or P-limited wheat plants commonly experience delayed leaf senescence, phasic development, and anthesis. P-stress stunts the growth and alters leaf numbers caused by restricted tiller development. P-deficiency has been shown to significantly stunt wheat growth under both glass-house and field experimental conditions, with the effect persisting until grain maturity resulting in a depressed grain yield and overall reduction in total plant biomass. When conditions of acute/moderate P-stress are experienced by *T. aestivum* and *T. durum*, resources are preferentially directed towards root growth (initially), whilst shoot growth is limited and delayed maximising the leaf : stem ratio (Elliott et al., 1997a). Severe P deficiency impacts the biomass or dry matter distribution between the roots and shoots of the plant and also between the conducting tissues (sheaths and stems) and leaf blades. These phenological responses intensify with advancing plant age (Elliott et al., 1997a, Elliott *et al.*, 1997b). Root growth, in both glass-house and field crops of wheat, is eventually depressed under P deficiency, which in turn leads to a poorer acquisition of other important nutrients, reduced water efficiency and drought tolerance.

Plant Tissue	Growth Stage	Growth Category	Critical Deficiency (% dry weight)	Adequate (% dry weight)	Notes/Reference
Whole Shoot	21 DAS	Seedling	-	0.79-1.04	Reuter *et al.* (1997)
	28 DAS	Seedling	0.8-0.9	-	Reuter *et al.* (1997)
	36 DAS	Seedling	-	0.53-0.65	Reuter *et al.* (1997)
	≤40 DAS	Early tillering	0.91±0.15	-	Reuter *et al.* (1997)
	41-60 DAS	Early tillering	0.55±0.03	-	Reuter *et al.* (1997)
	61-90 DAS	Tillering	0.44±0.05	-	Reuter *et al.* (1997)
	90+ DAS	Late till	0.23±0.03	-	Reuter *et al.* (1997)
	Late Till	Late till	0.2	>0.2	Reuter *et al.* (1997)
	ZS12-13.5/21	Seedling	0.59-.07	-	Reuter *et al.* (1997)
	ZS14.5/2+	Seedling	0.48-0.58	-	Reuter *et al.* (1997)
	ZS15.5/2+	Seedling	0.38-0.45	-	Reuter *et al.* (1997)
	ZS16.5/2+	Seedling	0.27-0.33	-	Reuter *et al.* (1997)
	ZS17.2/2+	Jointing	0.23-0.27	-	Reuter *et al.* (1997)
	ZS31	Jointing	0.18-0.22	-	Reuter *et al.* (1997)
	FS 10.1	Seedling	-	0.15-0.3	Reuter *et al.* (1997)
YEB	FS1	Seedling	-	0.3-0.8	Reuter *et al.* (1997)
	ZS12-13.5/21	Seedling	0.48-0.55	-	1st-3rd blade on main culm; Reuter et al. (1997)
	ZS14.5/2+	Seedling	0.44-0.47	-	4th blade on main culm; Reuter et al. (1997)
	ZS15.5/2+	Seedling	0.32-0.38	-	5th blade on main culm; Reuter et al. (1997)
	ZS16.5/2+	Seedling	0.24-0.3	-	6th blade on main culm; Reuter et al. (1997)
	ZS17.2/2+	Jointing	0.22-0.27	-	7th blade on main culm; Reuter et al. (1997)
	ZS31	Jointing	0.21-0.25	-	Reuter et al. (1997)
NG	<27 DAS	Seedling	-	-	Elliot *et al.* (1997c)
SFB	<27 DAS	Seedling	-	0.9	Elliot *et al.* (1997c)
SYEB	<27 DAS	Seedling	-	0.49 ± 0.05	Elliot *et al.* (1997c)
SYEB+1	<27 DAS	Seedling	-	0.24 ± 0.03	Elliot *et al.* (1997c)
SYEB+2	<27 DAS	Seedling	-	0.22 ± 0.04	Elliot *et al.* (1997c)
NG	>57 DAS	Mid to late till	-	-	Elliot *et al.* (1997c)
SFB	>57 DAS	Mid to late till	-	0.68 ± 0.06	Elliot *et al.* (1997c)

SYEB	>57 DAS	Mid to late till	-	0.25	Elliot *et al.* (1997c)
SYEB+1	>57 DAS	Mid to late till	-	0.14 ± 0.01	Elliot *et al.* (1997c)
SYEB+2	>57 DAS	Mid to late till	-	0.11 ± 0.01	Elliot *et al.* (1997c)
YMB	36 DAS	Seedling	0.39	-	Reuter et al. (1997)
	Mid to late Till	Mid to late till	-	0.3-.05	Reuter et al. (1997)
Grain	Mature	Mature	0.21-0.24	-	Critical range at max. grain yield
	Mature	Mature	~0.37	0.37-0.53	Grain P concentration vary with grain yield
	Mature	Mature	~0.4	-	Critical at 100% max. grain yield
	Mature	Mature	-	0.20-0.29	Reuter et al. (1997)
	>57 DAS	Mid to late till	-	0.35	Elliot *et al.* (1997c)
Glumes	>57 DAS	Mid to late till	-	0.15	Elliot *et al.* (1997c)
Straw	>57 DAS	Mid to late till	-	0.032	Elliot *et al.* (1997c)
Roots	<27 DAS	Seedling	-	0.75	Elliot *et al.* (1997c)

Table 5. Estimated critical total P concentrations (%) of wheat (*Triticum durum* and *Triticum aestivum*) tissues at different developmental stages of plant ontogeny for P-adequacy (27 mg P/Kg soil). Data taken from Elliot *et al.* (1997c) and Reuter *et al.* (1997). New growth (NG), folded blades (FB), youngest emerged blade (YEB), and successively older blades (YEB+1, YEB+2), sheath folded blades (SFB), sheath youngest emerged blade (SYEB), and successively older sheath blades (SYEB+1, SYEB+2). Growth stages define using Feeke's scale of growth stages in cereals, Zadok's decimal code for the growth stages of cereals and days after sowing (DAS)

Barley: *Hordeum vulgare*

Barley is often grown in rotation with other grain crops and pastures, and in intensive cropping scenarios, barley can also be in rotation with wheat crops. Phosphatic fertilisers are commonly applied to barley crops grown in southern Australia. Barley plants that experience P deficiency display necrosis of older leaves at later developmental phases. If P stress is maintained, necrosis had been found to extend down affected leaves to younger leaves. Severe P deficiency in barley crops results in depressed tillering and consequently reduced grain yield. Grain yield is principally due to reduced ear density, however, mean grain weight and mean number of grains per ear is also affected by severe P deficiency. Moderate P deficiency has similar impacts of reduced tillering and grain yield (Hoppo et al., 1999).

Plant Tissue	Growth Stage	Growth Category	Critical Deficiency	Adequate
Whole Shoot	42 DAS	Early tillering	0.41	-
	56 DAS	Early tillering	0.4	-
	70 DAS	Tillering	0.31	-
	ZS 13.5/21	Seedling	0.59-0.69	-
	ZS 14.5/2+	Seedling	0.48-0.58	-
	15.5./2+	Seedling	0.38-0.48	-
	16.5/2+	Seedling	0.28-0.38	-
YEB	ZS 13.5/21	Seedling	0.52-0.62	-
	ZS 14.5/2+	Seedling	0.43-0.53	-
	15.5./2+	Seedling	0.33-0.43	-
	16.5/2+	Seedling	0.24-0.34	-
YMB	Mid to late Till	Mid to late Till	-	0.3-0.5
Grain	Mature	Mature	0.19-0.26	-
Roots	-	-	-	-

Table 6. Estimated total P concentrations (%) of barley (*Hordeum vulgare*) tissues at different developmental stages of plant ontogeny for P-adequacy (27 mg P/Kg soil) and critical deficiency. Data taken from Reuter *et al.* (1997). Youngest emerged blade (YEB), and youngest mature blade (YMB). Growth stages define using Feeke's scale of growth stages in cereals, Zadok's decimal code for the growth stages of cereals and days after sowing (DAS)

Pastures:

Phosphorus stress is expressed in *Trifolium sp.* by the whole plant appears dark green and stunted with localized phosphorus stress expressed on older leaves initially. As the phosphorus stress is maintained an increase in anthocyanin is observed, cotyledons become chlorotic and necrotic, petioles become red and older leaves are chlorotic (Reuter et al., 1997).

Species	Young Tissue (P % dry weight)	Whole Shoots (P % dry weight)
Trifolium repens (White Clover)	0.30-0.34	0.25-0.3
Trifolium Subteraneum (Subterranean Clover)	0.30-0.40	0.28-0.32
Phalaris aquatica (Phalaris grass sp.)	0.20-0.25	0.18-0.20
Lolium perenne (Perennial Rye Grass)	0.20-0.28	0.20-0.25

Table 7. For *Phalaris* and *Lolium,* Young tissue: Young leaf blades collected when plants growing actively; Whole Shoots: Complete tillers collected when plant growing actively. For *Trifolium* sp. Young Tissue: Youngest open leaves collected during active growth, prior to flowering, Whole Shoot: Complete above ground growth collected prior to flowering. Data taken from Reuter *et al.* (1997).

Generalized tree (seedling, juvenile, mature): *Pinus radiata* and *Eucalyptus globules*

Phosphorus deficiency in *Eucalyptus globulus* initially can be identified by the appearance of small purple inter-veinal blotches on mature leaves. As the effects of P deficiency progress, the centre of each blotch become necrotic, turning white or brown. Symptoms progressively spread from mature to young leaves. In *E. globulus* the necrotic spots in severely P deficient trees coalesce into large areas of dead tissue, with irregularly shaped leaf margins. Severe P deficiency can lead to overall stunting of tree growth and foliage may turn purple (Dell et al., 2001). Phosphorus deficiency in *Pinus radiata* is most commonly expressed by the yellowing or browning of the pine needles, yet the tree generally remains green or grey green. A thin crown and fine branching is often displayed by juvenile pines with phosphorus deficiency. Fused needles, poor and uneven growth and resetting on some trees can occur, however for older trees under phosphorus stress, needle death is common with most loss occurring from the crown of the tree (Reuter et al., 1997).

Species	Growth Stage	Plant Part	Marginal (P%)	Adequate (P%)
Eucalyptus globulus	Seedling	NA	-	-
(Tasmanian Blue Gum)	Juvenile	YMF	0.12-0.14	0.14-0.26
	Mature	YMF	-	0.11-0.18
	Mature	New Leaf	-	0.057
	Mature	Twig <2 cm diameter	-	0.035
	Mature	Leaf litter	-	0.023±0.003
	Mean	Foliar	-	0.069±0.003b
Pinus radiata	Seedling	WS	0.09-0.14	0.177-0.344
(Plantation Pine sp.)	Juvenile	YMF	0.10-0.14	0.140.30
	Mature	YMF	0.10-0.14	0.14-0.30

Table 8. YMF: Young Mature Leaf. WS: Whole Shoot. All concentrations for *Eucalyptus globulus* are for irrigated plantations. Data taken from Judd *et al.* (1996)

A stand of trees (seedling, juvenile, mature): *Pinus radiata* and *Eucalyptus globulus*

At present, information for of the phosphorus requirements of a stand of trees has not been identified. It is recommended that research is undertaken to close the gap on forest dynamics

concerning nutrient content of a typical stand of trees in an Australian landscape. This must be accompanied by a definition of a typical stand of trees, incorporating stand age, average tree diameter at breast height (DBH) and tree height.

2.4.3 Typical plant nutrient (N & P) tissue contents

Tomato (*Solanum lycopersicum*) has been selected as a reference plant for illustrating typical plant nutrient tissue concentrations for both nitrogen and phosphorus. While tomato crops have high nutrient demands and could thus be thought of as an inappropriate reference crop, their selection is favoured by the high sensitivity in their plant tissues to nutrient concentrations caused by the surround soil solution and response to fertiliser additions, both with affect plant growth rate and nutrient supply (Reuter et al., 1997). The tables below provide a summary of critical deficiency, adequate and marginal plant tissue concentration values for different growth stages, spanning across a plants development.

Plant Tissue	Growth Stage	Critical Deficiency (% dry weight)	Adequate (% dry weight)	Marginal (% dry weight)
Whole Shoot	13 leaves	-	4.0-6.0	3.0-4.0
Youngest Mature Leaf (YML)	fl at 2nd node	-	5.5- 6.0	5.2-5.5
	1st mature fruit	3	4.0-6.0	-
	peak harvest	2	2.2-2.5	-
Youngest Open Leaf Blade (YOL)	28 DAT (fruit set 1st truss)	4.9	5.05	-
	42 DAT (flower 4th truss)	4.68	4.7	-
	56 DAT	4.75	4.81	-
	72 DAT (1st mature fruit)	4.45	4.9	-
	84 DAT	4.5	4.51	-
	98 DAT	-	5.14	-
Mature Fruit	peak harvest	3	3.4-3.8	-

Table 9. Nitrogen (%) concentrations in plant tissue for *Solanum lycopersicum*. Data sourced from (Reuter et al., 1997).

Plant Tissue	Growth Stage	Critical Deficiency (% dry weight)	Adequate (% dry weight)	Marginal (% dry weight)
Youngest Open Leaf Blade (YOL)	28 DAT	0.22	0.25	-
	42 DAT (flower 4th truss)	0.15	0.3	-
	56 DAT	0.08	0.12	-
	70 DAT	0.26	0.29	-
	84 DAT	0.2	0.3	-
	98 DAT	-	0.31	-
	112 DAT (final harvest)	-	0.29	-

Table 10. NO_3-N (%) concentrations in plant tissue for *Solanum lycopersicum*. Data sourced from (Reuter et al., 1997).

Plant Tissue	Growth Stage	Critical Deficiency (% dry weight)	Adequate (% dry weight)	Marginal (% dry weight)
Whole Shoot	13 leaves	-	0.65-1.20	0.40-0.65
Youngest Mature Leaf (YML)	fl at 2nd node	-	0.4-0.6	0.3-0.4
	1st mature fruit	0.3	0.4-0.8	-
	peak harvest	0.65	0.7-0.8	-
Youngest Open Leaf Blade (YOL)	28 DAT	-	0.98	-
	42 DAT (flower 4th truss)	-	0.98	-
	56 DAT	-	0.78	-
	70 DAT	-	0.85	-
	84 DAT	-	0.56	-
	98 DAT	-	0.8	-
	112 DAT (final harvest)	-	0.9	-
Mature Fruit	peak harvest	0.6	0.7-0.75	-

Table 11. P (%) concentrations in plant tissue for *Solanum lycopersicum*. Data sourced from (Reuter et al., 1997).

While tomato provides a good example of typical nutrient concentration of plant tissue, Epstein and Bloom (2005) have provided data that they suggest is representative of typical plant tissue concentrations for both nitrogen and phosphorus, which is summarised in Table 12. The disadvantage of using the typical plant tissue concentration values provided below is the uncertainty in the applicability of these values to the crop and native species found in Victoria. However, these values do provide a good basis for typical plant tissue nutrient concentrations.

Plant tissue	Nutrient concentration
Plant material	0.5-0.6 % (g N/g dry weight basis)
Grain	1.6-3.0 % (g N/g dry weight basis)
Plant material	0.15-0.5 % (g P/g dry weight basis)
Grain	0.2-0.5 % (g P/g dry weight basis)

Table 12. Generalised plant tissue nitrogen (N) and phosphorus (P) concentrations. Data taken from Epstein and Bloom (2005).

2.5 Review of the SWAT model and current use/limitations

Background - the SWAT model

The Soil and Water Assessment Tool (SWAT) is a catchment scale model that was developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS), in the early 1990s. SWAT was developed to predict the impacts of land management practices on environmental flows, water, sediment and agricultural chemical loadings across large catchments. It is a theoretical model that functions on a continuous time step (i.e. long-term yield model), incorporating the complexities of a landscape such as variation in soils, land use and management conditions (Neitsch *et al.*, 2005, Neitsch *et al.*, 2001). The primary objective and implementation of SWAT is the prediction of land-management practice influence on constituent yields from a catchment (Chaubey *et al.*, 2006). SWAT has also proven to be an effective tool for assessing water resource and nonpoint-source pollution problems across a range of scales and varying environmental conditions (e.g. Du *et al.*, 2009, Santhi *et al.*, 2001, Santhi *et al.*, 2005, Easton *et al.*, 2008, Sun & Cornish, 2006). As a result, SWAT is a globally employed simulation and assessment tool by government departments (e.g. Department of Sustainability and Environment) and catchment management authorities (Gassman *et al.*, 2007).

The SWAT model requires specific physical data such as soil properties, weather, topography, vegetation and management practices occurring within a catchment to develop models for physical processes such as nutrient cycling (refer to section 2.2), water and sediment movement (refer to section 2.3), crop growth (refer to section 2.4) etc. SWAT is a computationally efficient modelling system that can be used successfully for simulations for basins and catchments and management strategies (GalvÃ£o *et al.*, 2004, Santhi et al., 2001) without excessive time or financial investment (due to its open source nature). While SWAT can aid researchers in simulating and studying the long-term impacts of nutrient loading or gradual pollutant build-up, this requires data collection spanning decades. Nevertheless, where such data exist SWAT has been identified by this review as a good model and framework for interrogating such data to derive simulations.

SWAT allows for a number of different physical processes to be simulated in a catchment. For modelling purposes catchments are partitioned into sub-catchments or sub-basins. Input information is categorised within the sub-basin. Sub-basin divisions are particularly useful for simulation when catchments comprise several different land uses or soil types dissimilar enough in physical and chemical properties to impact hydrology. Sub-basins are further separated into Hydrologic Response Units (HRUs). HRUs consist of homogenous land use, soil characteristics and management, enabling detailed data to be collected and incorporated to develop the most accurate model of the entire catchment that accounts for the heterogonous nature of natural and managed systems, specifically the spatial heterogeneity of soils and land use within a catchment.

HRU divisions also enable modellers to differentiate and reference different areas of the catchment from one to another spatially (Neitsch et al., 2005, Neitsch et al., 2001, Gassman et al., 2007). Regardless of the problem of interest being studied with SWAT, water balance of the hydrological cycles in both the land and water/routing phases, is widely considered to be the main driving force behind all processes occurring in the catchment. The land phase of the hydrological cycle controls nutrient, sediment, water and pesticide loadings entering into the main channel in each sub-basin, whilst the water/routing phase focuses of the movement of the same attributes through the channel network to the outlet of the catchment. Sub-basin division increases accuracy and physical descriptions of the water balance, enabling a predictive model to incorporate and reflect differences found within the catchment (Neitsch et al., 2005).

The current SWAT model is an extension of the Simulator for Water Resources in Rural Basins (SWRRB). Several models have directly contributed to, and have been incorporated into SWAT expanding modelling capabilities, enabling long-term simulations that are spatially and temporally representative across catchments. Models such as Chemical, Runoff and Erosion for Agricultural Management Systems (CREAMS), Ground Water Loading Effects Agricultural Management Systems (GLEAMS) and Erosion-Productivity Impact Calculator (EPIC) have been incorporated into the SWAT model. Importantly SWAT can reportedly account for both point and non-point source pollutant loadings from catchments. CREAMS is a field scale model, designed to simulate the impacts of land management on sediments, nutrients, water and pesticides (Knisel, 1982), whereas GLEAMS is a nonpoint source model that is used to simulate pesticide and nutrient loadings in groundwater (Leonard *et al.*, 1987). EPIC has evolved into a comprehensive agricultural management model used at a field scale to simulate the impacts of erosion on crop productivity, nonpoint source loadings and pesticide application (Williams *et al.*, 1983). The Routing Outputs to Outlet (ROTO) model was developed in the early 1990s to creating a routing structure and was incorporated into SWAT. SWAT continues to incorporate new adaptations and modelling improvements as part of a continual trend of ongoing development (Gassman et al., 2007, Neitsch et al., 2005).

Current applications of SWAT

SWAT is widely used in the United States of America, Europe, Australia and Southeast Asian countries as a catchment management, assessment and biophysical simulation tool. The most current model SWAT2005 is used in three main areas of study: 1) climate; 2) crop management inputs and pollutant losses; and 3) flow and pollutant loss routing and auto-calibration and uncertainty analysis. The major application categories of SWAT include:

- Calibration and/or sensitivity analysis;
- Climate change impacts;
- GIS interface descriptions;

- Hydrological assessments;
- Variation in configuration or data input effects;
- Comparisons with other models or techniques; and
- Interfaces with other models
- Pollutant assessments.

Major modelling components of SWAT include soil temperature and properties, weather, hydrology, plant growth, bacteria and plant pathogens, nutrients, pesticides and land management. Climate input data is used to simulate and calculate precipitation and snowmelt, simulate climate change and forecast future weather patterns. SWAT is used to simulate the hydrological balance of each HRU with respect to water flows and redistribution between surface runoff and infiltration (water movement within the soil profile). Several Geographic Information Systems (GIS) and other interface tools have been developed to support input data such as topographic data, land use, soil and other digital data into SWAT to generate maps and models.

Data input parameters

Climate (Neitsch et al., 2005):

- Daily precipitation, maximum and minimum temperatures, solar radiation data, relative humidity, wind speed

Cropping, Management inputs, and HRU-level pollutant losses (Neitsch et al., 2005):

- Inorganic fertilizer and/or manure inputs;
- Biomass removal and manure deposition- type, rate, timing, efficiency and percentage;
- Manure application data;
- Management practices accounted for: terraces, strip cropping, contouring, grassed waterways, filter strips and conservation tillage;
- Water sources: stream, reach, reservoir, shallow aquifer, deep aquifer, or external catchment water source;
- Pesticide fate and transport: degradation and loss by volatilization, leaching, erosion with sediment, in solution with surface runoff and later subsurface flow; and
- Loss of N and P in soils by crop uptake and surface runoff (solution and erosion phases)

Flow and Pollutant loss routing and auto-calibration and uncertainty measures (Neitsch et al., 2005):

- Sediment, nutrient, pesticide and bacteria loadings (summed by HRU to sub-catchment level);
- Total flows and pollutant losses exported form each sub-catchment account of contributions from point source and urban areas;
- Losses are routed through channels, ponds, wetlands, depression areas and/or reservoirs to the catchment outlet;
- Peak channel velocity; and
- Channel erodibility factor

Data outputs

Climate (Neitsch et al., 2005):

- Simulate the hydrological balance for each HRU: canopy interception of precipitation, partitioning of precipitation, snowmelt water, irrigation water between surface runoff and infiltration, calculate the redistribution of water between soil profile layers, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers; and
- Forecast future weather patterns and climate change simulations

Cropping, Management inputs, and HRU-level pollutant losses (Neitsch et al., 2005):

- Estimate crop yields and/or biomass output (crop growth sub-model) for a range of crop rotations, grasslands/pasture systems and trees;
- Simulation of forest growth from seedling to mature stand;
- Simulation of planting, harvesting, tillage passes, nutrient application, and pesticide application (date specific or heat unit scheduling approach);
- Residue and biological mixing simulation in response to each tillage operation;
- Nitrogen and phosphorus application simulation;
- Simulation of confined animal feeding operations- frequency and quantity of manure addition to a HRU is specified;

- Irrigation application simulations to determine irrigation regimes and routines, determines catchment water stress thresholds;
- Water transfer between different water body simulations e.g. tile drainage, effects of land depressions;
- HRU-level and in-stream pollutant losses can be estimated for: sediment, nitrogen, phosphorus, pesticides and bacteria;
- Sediment yield calculations using the Modified Universal Soil Loss Equation (MUSLE, developed by Williams and Brendt, 1977) for comparative purposes only;
- Simulated transformation and movement of nitrogen and phosphorus within an HRU, as a function of nutrient cycles consisting of both inorganic and organic nutrient pools; and
- Simulation of bacteria surface runoff losses (solution and eroded phases)

<u>Flow and Pollutant loss routing and auto-calibration and uncertainty measures (Neitsch et al., 2005):</u>

- Sediment transport simulation through the catchement; and
- Simulation of channel erosion

Validation and assessment of SWAT for catchment management

There is a great need for calibration and validation methods for assessing catchment modelling tools. There is also a need to identify the criteria to achieve adequate validation (Green & van Griensven, 2008). Based on our review, it appears that these issues have not been adequately addressed in published scientific literature from Australia or internationally. While several validation and calibration publications for SWAT have been identified, only four publication from Australia have been identified (Sun & Cornish, 2005, Sun & Cornish, 2006, Watson *et al.*, 2003, Watson *et al.*, 2005), with the other literature predominantly from North America (e.g. Schilling & Wolter, 2009, Amatya *et al.*, 2008, Rosenthal & Garza, 2007, Santhi *et al.*, 2001) and the Mediterranean (e.g. Gikas *et al.*, 2006). The following section is a brief review of the Victorian validation publications, the consequential findings and subsequent recommendations.

Case study 1

A study conducted in Victoria, evaluated the water balance modelling capabilities of SWAT for the Woady Yaloak River catchment. The study, conducted by Watson *et al.* (2003), aimed to determine if SWAT is suitable for modelling the water balance of catchments in the southwest region of Victoria, and determine SWATs applicability as a planning tool to manage and predict the affects of land use change in large complex catchments. The study revealed that in the

Australia context, SWAT inadequately models groundwater and tree growth components, affecting its ability to accurately model water balance in Australian catchments. Woady Yaloak River catchment is dominated by agricultural land use including cropping (cereal crops) and livestock grazing (beef cattle and sheep). Large eucalyptus forests and plantation forest of both pine and eucalyptus species, and small residential and mining areas are also present within the catchment. The calibration and validation of streamflow model capabilities of SWAT were tested using calibration data collected in the period of 1978-1989 and the validation period of 1990-2001, using the divisions of surface runoff and base flow. Overall, annual streamflow predictions were very satisfactory for the two data collection stations used within the catchment, producing R^2 values of 0.75 and 0.86 for the calibration period, and 0.92 and 0.86 for the validation period (Watson et al., 2003). The calibration and validation periods where shown to have a comparatively good agreement with a 1:1 line for annual streamflow. The strength of the relationship between predicted and derived values interestingly increased when a monthly time scale was analysed. A major limitation of SWAT identified by this study is the groundwater model component, with SWAT tending to over-predicted base flows and recession rates, and hence underestimates soil interflows. Watson *et al.* (2003) attribute this to the routing delay caused by the simplistic runoff release feature used to 'lag' a portion of surface runoff released to the main channel, rather than routing overland flow, potentially affecting the recession rates. To be concise, the underlying simplicity of the groundwater model component of SWAT limits it accuracy in Australian catchments. Watson *et al.*'s (2003) application of SWAT to the Woady Yaloak River catchment demonstrated that groundwater cannot be accurately predicted in certain catchments using the current SWAT groundwater component due to the effects of seasonal flows not being appropriately accounted for in the application to dry land Australia typified by low flow hydrology. Watson *et al.* (2003) also found the simulation of growth of eucalyptus trees by SWAT to be inadequate. SWAT employs a simplified version of the EPIC plant growth component (Neitsch et al., 2001, Neitsch et al., 2005), with the outputs of total biomass (aboveground and roots) and Leaf Area Index (LAI). Inaccurate LAI simulation may contribute to the inaccuracy (overestimation) observed in the base and stream flow estimations. The problems that Watson *et al.* (2003) encountered with groundwater and tree growth components constrain the ability of SWAT to accurately model water balance in the Victoria context, however this study did demonstrate the excellent performance of SWAT for predicting annual streamflow.

Recommendations: groundwater and tree growth model components of SWAT must be modified to enable water balance modelling with greater accuracy in Australian catchments (Watson et al., 2003).

Case study 2

Another study was undertaken in Victoria at the Woady Yaloak River catchment, which aimed to evaluate the stochastic models used to generate the daily rainfall sequences needed to conduct long-term, continuous simulations with SWAT (Watson et al., 2003). This study evaluated the

performances of three daily rainfall generation models. The models evaluated were the modified Daily and Monthly Mixed (DMMm) model, skewed normal distribution (SKWD) model and modified exponential distribution (EXPD) model. The study assessed these models on their ability to preserve annual, monthly, and daily statistical characteristics of the historical rainfall and runoff. Watson *et al.* (2005) found that the mean annual, monthly, and daily rainfall was preserved adequately by these models. However, the DMMm model was found to reproduce the standard deviation of annual and monthly rainfall far better than the SKWD and EXPD models. Overall, the DMMm model performed only marginally better than the SKWD model at reproducing the statistical characteristics of the historical rainfall record at the various time scales. The performance of the EXPD model was found to be inferior to that of the DMMm and SKWD models. The models reproduced the mean annual, monthly, and daily runoff relatively well, yet the DMMm and SKWD models were found to preserve these statistics slightly better than the EXPD model. It is important to note that none of the models were found to reproduce the standard deviation of annual, monthly, and daily runoff adequately (Watson et al., 2005).

Evaluation of equations within SWAT2005

In addition to reviewing the application of SWAT (above) an assessment of key model components (selected in consultation with Mark Eigenramm and Wayne Lewis) now follows. This assessment includes a review of equations from the following sections: surface runoff (in brief), evapotranspiration (in brief), soil water (in brief), groundwater (recharge only), nitrogen, phosphorus, nutrient transport, growth cycle (in brief), optimal growth (in brief), actual growth (in brief). On the basis of this assessment a judgement as to whether or not the equations are adequate is provided. It is important to note that this assessment is based on available information identified in this review and as new knowledge is generated, it may be necessary to update this assessment. For the equations in SWAT that addressed nitrogen, phosphorus and nutrient transport, our process was to examine the key terms in the equation, to determine if appropriate variables were included. In this process strong emphasis was placed on peer review and validation of the equations, to evaluate how well the equation accounts for the theory behind the biological process being modelled. In the absence of peer reviewed equations, greater emphasis was placed on considering the key terms in the equations. For the equation sections in SWAT reviewed in brief, we placed a stronger emphasis on the theory used to establish the equations. With sections under brief evaluation we also placed strong emphasis on peer review and validation.

The following section will evaluate the equations found within the SWAT2005 model that are important and applicable to terrestrial nutrient cycling. The review of this section will take a conceptual approach to evaluating the biological validity of the components held within this chapter. A review of each equation will not be carried out, rather a brief examination of the concepts used to perform the analyses will be used to evaluate the equations.

Key criteria in the assessment include.

1) Peer review;

2) The terms in the equations are relevant to the process being modelled; and

3) Validation/calibration of each equation must be fulfilled for each output variable if they are to be used with confidence in prediction and simulation (Van Griensven & Bauwens, 2005).

The evaluation will include:

1) How well the modelling concepts can be applied in an Australian context; and

2) The limitations and advantages of the modelling concept

The following symbols have been used throughout section 2.5 within the table reviews of equations and the tables reviewing data availability:

Symbol	Meaning
✓	The data is available
×	The data is not available or identified in this review
?	The source of the data is unknown or not identified during this review
Limited	The data is available, however it was found in this review to be incomplete
Unknown	During the review, we were unable to determine the source or location of the data
N/A	Not applicable

SECTION 2 CHAPTER 1 SURFACE RUNOFF

<u>Section 2.1 Surface Runoff</u>

SWAT provides two methods for determining surface runoff; the SCS curve numbers procedure (SCS, 1972) and the Green & Ampt infiltration method (1911)

<u>2:1.1 Runoff Volume:</u>

<u>SCS curve number procedure 2:1.1.1.</u>

The SCS equation is an empirical model developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types. Curve numbers are a function of land use, soil's permeability and antecedent soil water conditions.

Limitations:

The SCS equation does not have an appropriate land use category for including natural vegetation cover types, nor does it account for fire damaged landscapes. In the section of agricultural activity, tilling practises are not accounted for in soil conditions for choosing the correct runoff curve number for the use in the equation.

SWAT2005 does not adjust curve numbers for slope; this must be done prior to entry of the curve number in the management input file.

Advantages:

Equations account for all aspects of water movement within the soil and overland influences on water additions to soils (infiltration, interception, abstractions, surface storage capacity, retention, topographic and management influences, initial soil water content).

Runoff only occurs if the daily rainfall exceeds the water infiltration and storage capacity of the soil.

Model uses three useful antecedent moisture conditions that are easily applied in a diversity of landscapes: dry (wilting point), average moisture, and wet (field capacity).

SWAT2005 allows user to select between two methods for calculating the retention parameters: the traditional method in which the retention parameter varies with the soil profile water content, and the alternative parameter offered in which SWAT2005 allows the retention parameter to vary with accumulated plant evapotranspiration. By calculating the daily curve number as a function of plant evapotranspiration the value is less dependent on soil storage and more depended on antecedent climate, reducing the risk of calculating too much runoff for shallow soils.

Frozen top soils are accounted for in the model. These however seem of limited relevance in Australia especially in a warming climate.

Review:

Hydrological soil groups are well defined for application in a global context, and are therefore considered adequate for use with Australian soils. Several constants are used in the equations for this section. These constants are based on peer reviewed studies which have been well validated, and are therefore considered adequate. All variables are available to SWAT users for the SCS equation.

Data Input Requirements	Availability	Source
Rainfall depth for the day (mm H_2O)	✓	BioSym, SILO & EnSym
Infiltration of water (mm H_2O)	✓	BioSym
Surface storage of water (mm H_2O)	✓	BioSym
Interception of water	✓	BioSym

Maximum value of retention that can be achieved on any day (mm)	✓	BioSym
Total soil water content (excluding wilting point) (mm H_2O)	✓	BioSym
Retention parameter of the previous day (mm d^{-1})	✓	BioSym
Weighting coefficient used to calculate the retention coefficient for the daily curve number calculation dependent of plant evapotranspiration	✓	BioSym

2:1.2 Runoff volume: Green & Ampt equation

The Green & Ampt equation was developed to predict infiltration assuming excess water at the surface at all times (Neitsch et al., 2005). The equation assumes the soil profile to be homogenous and antecedent moisture is uniformly distributed within the profile. Within SWAT this equation calculates the amount of water entering the soil on a sub-daily time step, water that does not infiltrate is considered runoff.

Limitations: Soils are not homogeneous, texture contrast soils may not work. Improved soil structure with increased soil C may be important.

Advantages:

Based on this review it appears that for native vegetation systems and fire affected landscapes the Green and Ampt equation set is more appropriate to use as it calculates runoff volume based on soil characteristics.

A ponding time with infiltration equation has been incorporated into the Green & Ampt method (Mein and Larson, 1973) as an alternative to calculating surface run-off; however it requires sub-daily precipitation data.

Hydrological conductivity of the soil equation is used to assist in assessing the soil moisture content and hence saturation of soil.

For each time step, SWAT calculates the amount of water entering into the soil, water that does not enter the soil is assumed to be surface runoff.

Review: The Green & Ampt method is considered applicable to Australian landscapes, and all variables are readily available to SWAT users for the Green & Ampt equations.

Data Inputs Required	Availability	Source
Saturated hydraulic conductivity (mm/hr)	✓	EnSym & BioSym
Soil porosity	✓	BioSym
Percent clay content of soil	✓	BioSym
Percent sand content of soil	✓	BioSym
Rainfall for the given time step (mm H_2O)	✓	EnSym & SILO

2.1.3 Peak Runoff Rate

Peak runoff rate is the maximum runoff that occurs with a rainfall event, and is used as an indicator of the erosive power of a storm event and used to predict runoff/ sediment loss. Peak runoff rate is calculated by SWAT with a modified rational method.

Limitations:

The unit conversion factor of 3.6 must be verified for use in an Australian context.

For calculating overland flow, Manning's roughness coefficient values does not have a value appropriate for accounting for forest plantations, native vegetation cover types (scrub, mallee, temperate rainforest, dry sclerophyll forest) or fire affected landscapes.

Advantages:

The rational method is widely used in the design of ditches, channels and storm water control systems

The equation used for calculating peak runoff use the sub-basin area rather than HRU area as sub-basins are geographically contiguous areas, making it easier to conceptualise. However, in the modelling process, SWAT is able to perform the calculations are the HRU level using simple modifications to the equations to transform scales.

SWAT2005 can model the time it takes for water entering the HRU to reach a channel.

Hydraulic considerations are used in equations, making them arguably more reliable than empirical equations.

Review: The Manning's roughness coefficients for characteristics of land surface must be checked to see if the limitations prior mentions are accounted for in SWAT, or there may be some issues uses these equation sets for Australian landscapes. Based on this review, the equations held within this section are considered adequate, and could be reasonably applied.

Data Inputs Required	**Availability**	**Source**
Average slope length (m)	✓	Ensym
Average slope steepness (m/m)	✓	EnSym
Area of sub-basin (km^2)	✓	EnSym
Fraction of sub-basin area contained in HRU	✓	EnSym
Manning's "n" value for overland flow	✓	Within SWAT
Daily rainfall data	✓	EnSym & SILO

2:1.4 Surface Runoff lag

SWAT2005 incorporates a surface storage feature to lag a portion of surface runoff released into the main channel, to account for delay in a large sub-basin where time of concentration is greater than one day.

Limitations: No major limitations identified in this review

Advantages: There are no specific advantages.

Review: The equations used to calculate surface runoff lag are considered adequate, there are no specific limitations or advantages that are associated with the equations. Based on this review, the equations appear to be broadly applicable to Australian landscapes and the data to perform the equations is readily available.

Data Inputs Required	Availability	Source
Surface runoff lag coefficient	✓	BioSym

2:1.5 Transmission Losses

Transmission losses of stream flow to ephemeral channels that occur in many arid or semi-arid catchments, reduce runoff volume as floodwaters travel downstream. SWAT incorporates a method of estimating transmission losses in the absence of observation data on inflow-outflow, and assumes no lateral inflow or out-of-bank flow contributions to runoff.

Limitations: No major limitations identified in this review.

Advantages:

Equations take into consideration the differences in channel width and length

Transmission losses are assumed to percolate to the shallow aquifer.

Review: Based on this review, it appears that the equations used to calculate transmission losses are widely applicable to Australian landscapes. Data that pertains to channel morphology may not be easily obtained in detail, to date this has it has not been identified in EnSym or BioSym.

Data Inputs Required	Availability	Source
Longest tributary channel length in subbassin (m)	Unknown	EnSym
Average width of tributary channel (m)	Unknown	EnSym
Area of sub-basin (km^2)	✓	EnSym
Fraction of sub-basin area contained in HRU	✓	EnSym
Effective hydraulic conductivity (mm/hr)	Unknown	EnSym & BioSym

SECTION 2 CHAPTER 2 EVAPOTRANSPIRATION

2.2.1 Canopy Storage equations

Limitations:

Unclear if leaf area index (LAI) is varied for different plant species.

Equations do not account for a canopy that has not reached maturity.

Equations do not account for drought impacts on total LAI for eucalyptus species that can reduce by 50-97% of pre-drought LAI (Pook, 1985).

Advantages: There are no specific advantages

Review: Only a limited amount of data is available for the LAI and it pertains only to a generalised leaf area, rather than differentiating between crop types, tree species etc. Based on this review, the equations otherwise appear to be broadly applicable and appropriate for use in Australian catchments.

Data Input Required	Availability	Source
Leaf Area Index for a given day	✓	BioSym
Maximum Leaf Area Index	✓	BioSym
Daily rainfall data (mm H_2O)	✓	EnSym & SILO

2.2.2 Potential evapotranspiration

Three methods are incorporated into SWAT to estimate potential evapotranspiration: the Pennman-Monteith method, the Priestly-Taylor method, and the Hargreaves method. The three methods vary in the amount and detail of data required to perform the analyses and simulations. The Pennman-Monteith method requires solar radiation, wind speed, air temperature and relative humidity data; the Priestly-Taylor method requires solar radiation, relative humidity, and air temperature data; and the Hargreaves method only requires air temperature data.

2.2.2.1 Pennman-Monteith evapotranspiration method

Limitations:

Currently the equation is solved for a reference crop species (reference species alfalfa), perhaps the equation should be modified for a native vegetation type eg. Eucalyptus forest, to broaden the application capabilities.

Detailed species specific data on stomatal distribution for several plant species would be required to effectively calculate canopy resistance equations.

The use of daily values can potentially lead to significant errors resulting from diurnal distributions of wind speed, humidity, and net radiation that in combination create conditions which the daily averages do not replicate.

Advantages:

Extensively validated and peer reviewed equations.

Equations can be used for climate change simulations as the canopy resistance term can be modified to reflect the impacts of a change in CO_2 concentrations on leaf conductance.

SWAT will default the value of CO_2 concentration to 330 ppmv if no value is entered by the user. Current concentrations are ~380ppmv

Threshold vapour pressure deficit is assumed to be 1.0 kPa for all plant species.

2.2.2.2 Preistly-Taylor Method

Limitations:

In arid or semi-arid areas where the advection component of the energy balance is significant, the Preistly-Taylor equation will underestimate potential evapotranspiration.

Advantages:

The Preistly-Taylor equation is simplified combination of equations for use when the surface areas are wet.

The Preistly-Taylor equation provides estimates of potential evapotranspiration for low advective conditions.

2.2.2.3 Hargreaves method

Limitations: Equation may be considered too simplistic.

Advantage: Only requires air temperature data.

Review: These sets of equations are extensively validated by peer reviewed articles, and have broad application capabilities in an Australian context. All the input variables required for the evapotranspiration section are available for SWAT users through SILO and EnSym. The Penman-Monteith equations are more complete and complex and all the input variables are available, however, under data limited scenarios the other methods are also reasonable for

application. The Penman-Monteith method also has a function that can be used in climate change scenarios.

Data Inputs Required	**Availability**	**Source**
Daily wind speed (m/s)	✓	SILO & EnSym
CO_2 concentration (ppmv)	✓	SILO & BioSym
Daily maximum temperature (°C)	✓	SILO & EnSym
Daily minimum temperature (°C)	✓	SILO & EnSym
Maximum leaf conductance (m s^{-1})	✓	BioSym
Net radiation (MJ m^{-2} d^{-1})	✓	SILO & EnSym
Heat flux density to the ground (MJ m^{-2} d^{-1})	✓	SILO & EnSym

2.2.3 Actual evapotranspiration

Actual evapotranspiration is calculated as a function of evaporation of intercepted rainfall, the maximum amount of transpiration and the maximum amount of sublimation/soil evaporation. When snow is present in the HRU then sublimation will occur, when no snow is present evaporation from the soil will take place.

Limitations:

Transpiration equations assume that plants are growing under ideal conditions.

Advantages:

Only once free water in the canopy has been evaporated can the remaining evaporative water demand be partitioned between vegetation and snow/soil.

The Pennman-Monteith method is used as the potential evapotranspiration method for use with actual evapotranspiration.

The degree of shading (soil cover index), is taken into consideration in equations examining sublimation and evaporation from soil, which is particularly important when modelling for catchment regions in the Victorian Alpine regions.

SWAT accounts for depth water distribution between the different soil layers, by accounting for different evaporative demands at the upper and lower boundaries of the soil layers (assumes that 50% of the evaporative demand is met by the soil water stored in the top 10 mm of the soil profile.

The user can modify the depth distribution used to meet the soil evaporative demands using a coefficient incorporated into the equations.

Evaporative demand equations can account for soils that have a water content of a soil layer that is below field capacity.

Review: The equations addressing actual evapotranspiration are thorough and explicit, accounting for all the major processes that effect and influence soil water evaporation. The inclusion of snow affected regions is especially important to Victorian Alpine regions. The equations can be used for Australian catchments. Major criticisms would be the inability of SWAT to again include the impacts of fire affected landscapes on soil water evapotranspiration and the differentiation between crop and native forest cover regions.

Data Inputs Required	Availability	Source
Leaf Area Index	Limited	BioSym
Soil water content of layer (mm H_2O)	✓	BioSym
Water content of soil layer at wilting point (mm H_2O)	✓	BioSym
Water content of soil layer at field capacity (mm H_2O)	✓	BioSym
Amount of water in snow pack on a given day prior to accounting for sublimation (mm H_2O)	Not Available	SILO ?
Transpiration on a given day (mm H_2O)	✓	EnSym
Evaporation on a given day (mm H_2O)	✓	EnSym

SECTION 2 CHAPTER 3 SOIL WATER

The movement of water within the soil profile moves along several different pathways. Water may be removed by plant uptake, water can percolate ultimately becoming aquifer recharge, or water can move laterally through the soil profile and contribute eventually to streamflow.

2:3.1 Soil Structure

SWAT accounts for each of the three soil phases – solid phase that consists of mineral and/or organic matter; the liquid and gas phases in soil occur between the solid soil particles in soil pores.

Limitations:

Data pertaining to soil texture and soil moisture conditions held within the SWAT model are based on soils from the United States of America.

Advantages:

All major components relating to soil structure are incorporated extensively into the SWAT model.

SWAT directly simulates saturated flow only, water is assumed to be uniformly distributed within a given soil layer, eliminating the need to model unsaturated flow in a horizontal direction. Unsaturated flow between layers is indirectly modelled with a depth distribution of plant water uptake (see Section 5 Chapter 2, equation 5:2.2.1) and depth distribution of soil water evaporation (see Section 2 Chapter 2, equation 2:2.3.16).

SWAT assumes no water movement when soil layer is frozen.

Review: The equations for soil structure are biologically valid; however, the data pertaining to soil moisture and soil texture conditions that are held within the SWAT model must be validated or changed to suit Australian soils.

Data Inputs Required	Availability	Source
Water content of soil at wilting point (mm H_2O)	✓	BioSym
Water content of soil at field capacity (mm H_2O)	✓	BioSym
Water content of soil at saturation (mm H_2O)	✓	BioSym
Soil texture (% sand, clay, loam)	Not Available	-
Soil bulk density data (Mg m^{-3})	✓	BioSym

2:3.2 Percolation

Percolation is calculated in SWAT2005 for each soil layer in the profile.

Limitations: No major limitations were identified in this review

Advantages:

Water is allowed by the model to percolate if the water content exceeds field capacity water content for the soil layer, and the soil layer below is not saturated.

When the soil layer is frozen, it is assumed that no water flow out of the layer occurs and is hence not calculated.

For HRUs with a seasonal high water table, percolation is limited by an upper value boundary; above this value the water will stay ponded in the upper layer.

SWAT2005 accounts for water movement into the vadose zone.

Review: Based on this review, these equations appear to be suitable for use with Australian soils.

Data Inputs Required	Availability	Source
Water content of soil layer at field capacity (mm H_2O)	✓	BioSym
Saturated hydraulic conductivity for the layer ($mm\cdot h^{-1}$)	✓	BioSym

2:3.3 Bypass Flow

Specifically incorporated into the SWAT model to account for Vertisols or cracking clays, these equations take into consideration a range of wetting and drying conditions. Bypass flow is defined as the vertical movement of free water along macropores through unsaturated soil horizons occurring under dry soil conditions. Bypass flow occurs when the rate of rainfall or irrigation exceeds the vertical infiltration rate into the soil peds.

SWAT calculates the crack volume of the soil matrix for each day of simulation by layer to model bypass flow.

Limitations: Constants used within the equations must be validated for use with Australian soils.

Advantages:

Surface runoff in excess of the crack volume remains modelled as overland flow.

A volume of water equivalent to crack volume for the soil profile may enter the soil as bypass flow.

Crack volume calculations for filling occur sequentially as each layer is filled.

Review: Based on this review, these equations can be applied to Australian soils, and Australian soils have been considered during model development of this section of SWAT2005. Vertisols are common to Australia, thus it is important that these equations are incorporated into the model.

Data Inputs Required	Availability	Source
Water content of soil layer at field capacity (mm H_2O)	✓	BioSym
Water content of soil layer on a given day (mm H_2O)	✓	BioSym
Adjustment coefficient for crack flow	✓	BioSym
Maximum crack volume possible for the soil layer (mm)	✓	BioSym

2:3.4 Perched Water Table

A perched water table is when water ponds in the soil profile, it occurs in an HRU with a seasonal high water table under conditions which the soil profile becomes saturated and percolation from upper to lower soils layers is inhibited.

Limitations: No major limitations were identified in this review

Advantages:

User can define the depth to an impervious layer for the HRU, which determines if water is allowed to percolate out of the soil profile layer, and allows for adjustment within the equations.

Saturation of soil profile layers is sequentially modelled in SWAT, with deepest soil layers reaching saturation before preceding layers.

Review: These equations can readily be used for Australian soils, however the constants used in the equations must be validated for Australian soils.

Data Inputs Required	Availability	Source
Water content of soil layer at field capacity (mm H_2O)	✓	BioSym
Water content of soil layer on a given day (mm H_2O)	✓	BioSym
Porosity of the soil profile (mm)	Not Available	-
Depth to impervious layer (mm)	Limited	BioSym

2:3.5 Lateral Flow

Lateral flow is assumed to be a significant process for soils with high hydraulic conductivities in surface layers and an impermeable or semi-permeable layer at a shallow depth. Lateral subsurface flow is sourced from water in a saturated zone, where ponding has occurred (e.g. a perched water table).

Limitations: No major limitations were identified in this review

Advantages:

Equations derived from peer reviewed articles.

An equation is incorporated to account for lag time effects in large catchments.

Review: These equations are broadly applicable to Australian catchments and soils. The constants in the equations, although they are taken from peer reviewed articles, must be verified for Australian soils.

Data Inputs Required	**Availability**	**Source**
Water content of soil layer at field capacity (mm H_2O)	✓	BioSym
Water content of soil layer on a given day (mm H_2O)	✓	BioSym
Total porosity of the soil profile (mm)	Not Available	-
Porosity of the soil layer filled with water when layer is at field capacity water content (mm/mm)	Not Available	-
Saturated hydraulic conductivity for the layer ($mm \cdot h^{-1}$)	Not Available	-
Hillslope length (m)	✓	BioSym
Drain tile lag time (hrs)	Not Available	-

Overall review: Based on this review, the soil water equations held within this section are on the most part broadly applicable to Australian soils and on the most part are derived from peer reviewed research. However, the issue of soil water salinity has not been addressed. It must be checked that salinity issues can be accounted for, for modelling purposes in Australian and specifically Victorian catchments that are, or in the future may be affected by rising salts.

SECTION 2 CHAPTER 4 GROUNDWATER

Water enters groundwater primarily through processes of infiltration and percolation, although recharge by seepage from surface water bodies can also occur. Water generally leaves groundwater storage by discharge into rivers or lakes, however capillary action can draw water upward.

2:4.2.1 Recharge

Water is considered recharge if it is water that moves past the lowest depth of the soil profile by percolation, infiltration or bypass flow and flows through the vadose zone before coming to a shallow and/or deep aquifer.

Limitations: No major limitations were identified in this review

Advantages:

SWAT enables the model to account for lag time in aquifer recharge once water exits the soil profile, accommodating situations where recharge is not instantaneous.

Once time delays have been established for one geographic region, adjoining areas can use similar delay times.

Review: Based on this review, the equations addressing groundwater recharge are applicable to Australian soils and are derived from peer reviewed research, and can thus be used with confidence in their accuracy.

Data Inputs Required	Availability	Source
Total amount of water exiting the bottom of the soil profile (mm H_2O)	✓	BioSym
Delay time for aquifer recharge	Not Available	-

Evaluation of equations within SWAT2005

The following section will evaluate the biological validity of the equations found within the SWAT2005 model that are important and applicable to terrestrial nutrient cycling.

For each equation the following will be outlined:

1) What are the capabilities of the equation?

2) Is the equation appropriate for the Australian landscape?

3) Are specific concepts important in an Australian context not included or accounted for by the equation?

4) Is the input data required for the equation readily available?

SECTION 3.1 Nitrogen

3:1.1.1 Initialization of soil nitrogen levels

Equation 3:1.1.1

$$NO3_{conc,z} = 7 \cdot exp\left(\frac{-z}{1000}\right)$$

Defining the terms:

$NO3_{conc,z}$ is the concentration of nitrate in the soil at depth z (mg/kg or ppm), and z is the depth from the soil surface (mm)

Evaluation:

1) Determines the initial concentration of nitrate (mg/kg or ppm) in the soil, at a given depth from the soil surface (mm) if the user has not defined the amount of nitrate and organic N contained in the humic substances for all soil layers prior to simulation. Uses the soil horizons lower boundary depth to solve the equation for each soil layer.

2) As it is not a landscape specific equation, it can be applied and generalised for Australian use.

3) This equation requires that the initialisation values used in the equation are corrected for Australian use. This means that the values that are currently held within SWAT from studies undertaken in the United States of American are not appropriate for application, and hence the coding should be changed to use Australia values.

4) The data is limited in availability for correcting the initialisation nitrate values for this equation. Further work needs to be undertaken to determine the correct input values for Australian soils.

Equation 3:1.1.2

$$orgN_{hum,ly} = 10^4 \cdot \left(\frac{orgC_{ly}}{14}\right)$$

Defining the terms:

$orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the later (mg/kg or ppm), and $orgC_{ly}$ is the amount of organic carbon in the layer (%).

Evaluation:

1) Determines the concentration of humic organic nitrogen (mg/ok or ppm) in the soil layer.
2) As it is not a landscape specific equation, it can be applied and generalised for Australian use.
3) The C:N ratio of 14:1 is assumed for humic material in this equation, it must be confirmed that this ratio is correct for Australian soils.
4) This equation requires the input of the amount of organic C in the layer (%) or soil being examined. EnSym provides total carbon stored per ha.

Equation 3:1.1.3

$$orgN_{act,ly} = orgN_{hum,ly} \cdot fr_{actN}$$

Defining the terms:

$orgN_{act,ly}$ is the concentration of nitrogen in the active organic pool (mg/kg), $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg), and fr_{actN} is the fraction of humic nitrogen in the active pool (set to 0.02).

Evaluation:

1) Determines the concentration of nitrogen in the active organic pool (mg/kg).
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) It must be confirmed that the set fraction (0.02) humic nitrogen in the active pool is accurate.

4) EnSym provides data to calculate $orgN_{hum.ly}$ (equation 3:1.1.2) and the set fraction is provided by SWAT, data is therefore available.

Equation 3:1.1.4

$$orgN_{sta,ly} = orgN_{hum,ly} \cdot (1 - fr_{actN})$$

Defining the terms:

$orgN_{sta,ly}$ is the concentration of nitrogen in the stable organic pool (mg/kg), $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg) (equation 3:1.1.2), and fr_{actN} is the fraction of humic nitrogen in the active pool (set to 0.02).

Evaluation:

1) Determines the concentration of nitrogen in the stable organic pool (mg/kg)
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) It must be confirmed that the set fraction (0.02) humic nitrogen in the active pool is accurate.
4) EnSym provides data to calculate $orgN_{hum.ly}$ and the set fraction is provided by SWAT, data is therefore available.

Equation 3:1.1.5

$$orgN_{frsh,surf} = 0.0015 \cdot rsd_{surf}$$

Defining the terms:

$orgN_{frsh,surf}$ is the nitrogen in the fresh organic pool in the top 10 mm (kg N/ha), rsd_{surf} is material in the residue pool for the top 10mm of the soil (kg/ha).

Evaluation:

1) Determines the concentration of nitrogen in the fresh organic pool in the top 10 mm of soil, which is set to 0.15% of the initial amount of reside on the soil surface.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) It must be confirmed that estimating the fresh organic pool as the top 10 mm is accurate for Australian soils, and that the initial residue setting of 0.15% is suitable.
4) Data for material residue pool is not readily available in EnSym or BioSym.

Equation 3:1.1.6

$$\frac{conc_N \cdot \rho_b \cdot depth_{ly}}{100} = \frac{kg\ N}{ha}$$

Defining the terms:

$conc_N$ is the concentration of nitrogen in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm)

Evaluation:

1) Determines the amount of nitrogen (kg) per hectare. This equation allows the conversion of nutrient concentrations to mass.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) There are no specific elements missing for this equation
4) Bulk density of soil layers and layer depth information is available through EnSym and the relevant soil codes per scenario and cell.

3:1.2 Mineralization & decomposition/immobilization

Equation 3:1.2.1

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + exp[9.93 - 0.312 \cdot T_{soil,ly}]} + 0.1$$

Defining the terms:

$\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, and $T_{soil,ly}$ is the temperature of the layer *ly* (ºC). The nutrient cycling factor is never allowed to fall below 0.1.

Evaluation:

1) Determines the nutrient cycling temperature for the mineralisation and decomposition equations.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) No terms are absent, however the values must be must be checked for suitability in an Australian environment.

4) Soil temperature data is not readily available in EnSym. Generalised soil temperature data, which would not be sufficiently accurate, is available in the BioSym database.

Equation 3:1.2.2

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}}$$

Defining the terms:

$\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*, SW_{ly} is the water content layer on *ly* on a given day (mm H_2O), and FC_{ly} is the water content of the layer *ly* at field capacity (mm H_2O). The nutrient cycling water factor is never allowed to fall below 0.05.

Evaluation:

1) Determines the nutrient cycling water factor for the mineralisation and decomposition equations.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no specific terms were identified as absent.

4) EnSym provides rainfall (mm), surface runoff, evaporation (actual and pan) and soil classification data (reference). BioSym calculates soil water daily and data on soil field capacity water content is held in the soils database.

<u>3:1.2.1 Humus mineralization</u>

Equation 3:1.2.3

$$N_{trns,ly} = \beta_{trns} \cdot orgN_{act,ly} \cdot \left(\frac{1}{fr_{actN}} - 1\right) - orgN_{sta,ly}$$

Defining the terms:

$N_{trns,ly}$ is the amount of nitrogen transferred between the active and stable organic pools (kg N/ha), β_{trns} is the rate constant (1 x 10^{-5}), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha), fr_{actN} is the fraction of humic nitrogen in the active pool (0.02), and $orgN_{act,ly}$ is the amount of nitrogen in the stable organic pool (kg N/ha).

Evaluation:

1) Determines the amount of nitrogen transferred from one pool to the other: active to stable. When $N_{trns,ly}$ is a positive value, nitrogen is moving from the active organic pool to

the stable organic pool. When $N_{trns,ly}$ is negative, nitrogen is moving from the stable organic pool to the active organic pool.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) The constant rate (1 x 10^{-5}) and the fraction of humic nitrogen in the active pool (0.02) must be verified as suitable for Australian soils.

4) EnSym provides data to calculate equation 3:1.1.2, therefore the calculation of $orgN_{act,y}$ and $orgN_{sta,ly}$ is possible, hence the equation can be solved using available data.

Equation 3:1.2.4

$$N_{mina,ly} = \beta_{\min} \cdot (\gamma_{tmp,ly} \cdot \gamma_{sw,ly})^{\frac{1}{2}} \cdot orgN_{act,ly}$$

Defining the terms:

$N_{mina,ly}$ is the nitrogen mineralized from the humus active organic N pool (kg N/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for the layer *ly* (equation 3:1.2.1), $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* (equation 3:1.2.2), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha) (equation 3:1.1.3).

Evaluation:

1) Determines the amount of nitrogen mineralized from the humus active organic N pool. This equation requires the information derived from equations 3:1.2.1 and 3:1.2.2, and cannot be carried out prior to the solving of these equations.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent

4) EnSym provides sufficient data to calculate equation 3:1.1.2, therefore the calculation of $orgN_{act,y}$. Generalised soil temperature data, which would not be sufficiently accurate, is available in the BioSym database.

<u>3:1.2.2 Residue decomposition & mineralization</u>

Equation 3:1.2.5

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}}$$

Defining the terms:

$\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, rsd_{ly} is the residue in the layer *ly* (kg/ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer *ly* (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer *ly* (kg N/ha).

Evaluation:

1) Determines the C:N ratio of the residue for the soil layer. This equation is used to calculate the decay rate constant which controls decomposition and mineralization processes of the fresh organic nitrogen pool in the first soil layer

2) This equation is suitable for use in Australian soils, providing that the C residue fraction value is accurate. Although no reference has been made, 0.58 is the van Bemmelen conversion factor used to determine the soil organic carbon content of organic material. Whilst not being a precise value, it can be employed with reasonable accuracy.

3) Need to verify if 0.58 is the correct fraction of residue that is carbon for Australian soils.

4) EnSym does not supply data on the nitrogen status of the soils or the residue in the soil layer. Basic nitrogen data for top and sub soils is available in the BioSym database.

Equation 3:1.2.6

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}}$$

Defining the terms:

$\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer, rsd_{ly} is the residue in the layer *ly* (kg P/ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in the layer *ly* (kg P/ha).

Evaluation:

1) Determines the C:P ratio of the residue for the soil layer. This equation is used to calculate the decay rate constant which controls decomposition and mineralization processes of the fresh organic nitrogen pool in the first soil layer

2) Based on this review, this equation is suitable for use in Australian soils, providing that the C residue fraction value is accurate.

3) Need to verify if 0.58 is the correct fraction of residue that is carbon for Australian soils.

4) Soil phosphorus content data is available through BioSym.

Equation 3:1.2.7

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot (\gamma_{tmp,ly} \cdot \gamma_{sw,ly})^{\frac{1}{2}}$$

Defining the terms:

$\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly* (equation 3:1.2.1), and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* (equation 3:1.2.2).

Evaluation:

1) Determines the decay rate constant, using values derived from equations 3:1.2.1 (nutrient cycling temperature), 3:1.2.2 (nutrient cycling water factor).
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) Soil temperature data is not available for equation 3:1.2.1 with sufficient accuracy, but data is available for equation 3:1.2.2.

Equation 3:1.2.8

$$\gamma_{ntr,ly} = min \begin{cases} exp\left[-0.693 \cdot \frac{(\varepsilon_{C:N} - 25)}{25}\right] \\ exp\left[-0.693 \cdot \frac{(\varepsilon_{C:P} - 200)}{200}\right] \\ 1.0 \end{cases}$$

Defining the terms:

$\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, $\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer.

Evaluation:

1) Determines the nutrient cycling residue composition factor, using the values derived from equations 3:1.2.5 (C:N ratio of the residue in the soil layer) and 3:1.2.6 (C:P ratio of the residue in the soil layer).
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Data not readily available

Equation 3:1.2.9

$$N_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgN_{frsh,ly}$$

Defining the terms:

$N_{minf,ly}$ is the nitrogen mineralized from the fresh organic N pool (kg N/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer *ly* (kg, N/ha).

Evaluation:

1) Calculates the mineralization from residue fresh organic N pool. Nitrogen mineralized from the fresh organic pool is added to the nitrate pool in the layer. Requires values from equation 3:1.2.7 (residue decay rate constant).

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Nitrogen content of the fresh organic pool data is available in BioSym.

<u>**3:1.3 Nitrification and Ammonia volatilization**</u>

The following four equations are used by SWAT to derive coefficients for the nitrification/volatilization algorithms to account for the impact of soil temperature, soil water content, and depth and cation exchange capacity of the soil.

Equation 3:1.3.1

$$\eta_{tmp,ly} = 0.41 \cdot \frac{(T_{soil,ly} - 5)}{10} \qquad \text{if} \qquad T_{soil,ly} > 5$$

Defining the terms:

$\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor, and $T_{soil,ly}$ is the temperature of the layer *ly* (°C).

Evaluation:

1) Determines the coefficient for the nitrification/volatilization temperature factor.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Generalised soil temperature data for top and sub soil is available in the BioSym database, however this data is not sufficiently accurate or applicable for all soils.

Equation 3:1.3.2

$$\eta_{sw,ly} = \frac{SW_{ly} - WP_{ly}}{0.25 \cdot (FC_{ly} - WP_{ly})} \quad \text{if} \quad SW_{ly} > 0.25 \cdot FC_{ly} - 0.75 \cdot WP_{ly}$$

$$\eta_{sw,ly} = 1.0 \qquad \text{if} \quad SW_{ly} \geq 0.25 \cdot FC_{ly} - 0.75 \cdot WP_{ly}$$

Defining the terms:

$\eta_{sw,ly}$ is the nitrification soil water factor, SW_{ly} is the soil water content of layer *ly* on a given day (mm H_2O), WP_{ly} is the amount of water held in the soil layer at wilting point water content (mm H_2O), and FC_{ly} is the amount of water held in the soil layer at field capacity water content (mm H_2O).

Evaluation:

1) Determines the coefficient for the nitrification soil water factor

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Generalised soil temperature data for top and sub soil is available in the BioSym database, however this data is not sufficiently accurate or applicable for all soils.

Equation 3:1.3.4

$$\eta_{midz,ly} = 1 - \frac{z_{mid,ly}}{z_{mid,ly} + exp[4.706 - 0.0305 \cdot z_{mid,ly}]}$$

Defining the terms:

$\eta_{midz,ly}$ is the volatilization depth factor, and $z_{mid,ly}$ is the depth from the soil surface to the middle of the layer (mm).

Evaluation:

1) Determines the volatilization depth factor

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) EnSym is able to provide soil depth, layer and profile depth information.

Equation 3:1.3.5

$\eta_{cec,ly} = 0.15$

Defining the terms:

$\eta_{cec,ly}$ is the volatilization catio**n exchange facto**r constant.

Evaluation:

1) This equation is the volatilization cation exchange factor, set as a constant value for use in the SWAT model, as SWAT does not require the used to provide this information

2) This equation is suitable for use with Australian soils.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) N/A

Equation 3:1.3.6

$\eta_{nit,ly} = \eta_{tmp,ly} \cdot \eta_{sw,ly}$

Defining the terms:

$\eta_{nit,ly}$ is the nitrification regulator, $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor (3:1.3.1), $\eta_{sw,ly}$ is the nitrification soil water factor (3:1.3.2 and 3:1.3.3), and is the volatilization depth factor (3:1.3.4).

Evaluation:

1) Determines the nitrification regulator, to evaluate the impact of environmental factors on nitrification.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Not clear if EnSym can provide the data required for all equations, further interrogation required.

Equation 3:1.3.7

$$\eta_{vol,ly} = \eta_{tmp,ly} \cdot \eta_{midz,ly} \cdot \eta_{cec,ly}$$

Defining the terms:

$\eta_{vol,ly}$ is the volatilization regulator, $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor (3:1.3.1), $\eta_{midz,ly}$ is the volatilization depth factor (3:1.3.4), $\eta_{cec,ly}$ is the volatilization cation exchange factor constant (3:1.3.5).

Evaluation:

1) Determines the volatilization regulator, to evaluate the impact of environmental factors on volatilization.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Not clear if EnSym can provide the data required for all equations, further interrogation required.

Equation 3:1.3.8

$$N_{(nit|vol,ly)} = NH4_{ly} \cdot (1 - exp[-\eta_{nit,ly} - \eta_{vol,ly}])$$

Defining the terms:

$N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha), $NH4_{ly}$ is the amount of ammonium in layer *ly* (kg N/ha), $\eta_{nit,ly}$ is the nitrification regulator (3:1.3.6) $\eta_{vol,ly}$ is the volatilization regulator (3:1.3.7).

Evaluation:

1) Determines the total amount of ammonium lost to nitrification and volatilization, calculated using a first-order kinetic rate equation.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Ammonium per soil layer data is not available in EnSym. Also not clear if EnSym can provide the data required for equations 3:1.3.6 and 3:1.3.7, further interrogation required.

Equation 3:1.3.9

$$fr_{nit,ly} = 1 - exp\lfloor -\eta_{nit,ly} \rfloor$$

Defining the terms:

$Fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification, $\eta_{nit,ly}$ is the nitrification regulator (3:1.3.6).

Evaluation:

1) Determines the fraction of ammonium removed by nitrification.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Data not readily available for equation 3:1.3:6.

Equation 3:1.3.10

$$fr_{vol,ly} = 1 - exp\lfloor -\eta_{vol,ly} \rfloor$$

Defining the terms:

$fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization, $\eta_{vol,ly}$ is the volatilization regulator (3:1.3.7).

Evaluation:

1) Determines the fraction of ammonium removed by volatilization.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Not clear if EnSym can provide the data required for all equations, further interrogation required.

Equation 3:1.3.11

$$N_{nit,ly} = \frac{fr_{nit,ly}}{(fr_{nit,ly} + fr_{vol,ly})} \cdot N_{(nit|vol,ly)}$$

Defining the terms:

$N_{nit,ly}$ is the amount of nitrogen converted from NH_4^+ to NO_3^- in layer *ly* (kg N/ha), $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification (equation 3:1.3.9), $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization (equation 3:1.3.10), and $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha) (equation 3:1.3.8).

Evaluation:

1) Determines the amount of nitrogen converted from NH_4^+ to NO_3^-, by calculating the amount of nitrogen removed from the ammonium pool by nitrification for each soil layer.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Not clear if EnSym can provide the data required for all equations, further interrogation required.

Equation 3:1.3.12

$$N_{nit,ly} = \frac{fr_{vol,ly}}{(fr_{nit,ly} + fr_{vol,ly})} \cdot N_{(nit|vol,ly)}$$

Defining the terms:

$N_{voly,ly}$ is the amount of nitrogen converted from NH_4^+ to NH_3 in layer *ly* (kg N/ha), $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification (equation 3:1.3.9), $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization (equation 3:1.3.10), and $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha) (equation 3:1.3.8).

Evaluation:

1) Determines the amount of nitrogen converted from NH_4^+ to NH_3, by calculating the amount of nitrogen removed from the ammonium pool by volatilization for each soil layer.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation, to determine if they are suitable for Australian soils.

4) Not clear if EnSym can provide the data required for all equations, further interrogation required.

<u>3:1.4 Denitrification</u>

Equation 3:1.4.1 and 3:1.4.2

$$N_{denit,ly} = NO3_{ly} \cdot (1 - exp[-\beta \cdot \gamma_{tmp,ly} \cdot orgC_{ly}]) \text{ if } \gamma_{sw,ly} \geq \gamma_{sw,thr}$$

$$N_{denit,ly} = 0.0 \qquad \text{if } \gamma_{sw,ly} < \gamma_{sw,thr}$$

Defining the terms:

$N_{denit,ly}$ is the amount of nitrogen lost to denitrification (kg N/ha), $NO3_{ly}$ is the amount of nitrate in the layer *ly* (kg N/ha) (equation 3:1.1.1.), β_{denit} is the rate coefficient for denitrification, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly* (equation 3:1.2.1), $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* (equation 3:1.2.2), $orgC_{ly}$ is the amount of organic carbon in the layer (%), and $\gamma_{sw,thr}$ is the threshold value of nutrient cycling temperature factor for denitrification to occur.

Evaluation:

1) Determines the amount of nitrate lost to denitrification, as denitrification is a function of water content, temperature, presence of a carbon source and nitrate. An important equation for use in agricultural systems that are flood irrigated or ponded, where a large proportion of fertilizer can be lost by denitrification (up to approx. 50%).

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Need verification for the values used in the equation to determine if they are suitable for Australian soils.

4) EnSym provides information on organic carbon content for soil per hectare.

3:1.5 Nitrogen in rainfall

Equation 3:1.5.1

$$N_{rain} = 0.01 \cdot R_{NO3} \cdot R_{day}$$

Defining the terms:

N_{rain} is nitrate added by rainfall (kg N/ha), R_{NO3} is the concentration of nitrogen in the rain (mg N/L), and R_{day} is the amount of precipitation on a given day (mm H_2O).

Evaluation:

1) Determines the amount of nitrate added to the soil in rainfall. The nitrogen in rainfall is added to the nitrate pool in the top 10mm of soil.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) Daily precipitation data is available within the SILO database, and annual averages from a daily time step are held within EnSym. Daily nitrogen concentration of rainfall data is available in BioSym, however this needs to be validated for Australia.

3:1.6 Fixation

Equation: No specific equation is provided in the nitrogen component of SWAT, as it is included in chapter 15 as a component of plant growth under nitrogen fixation of legumes

3:1.7 Upward movement of nitrate in water

Equation 3:1.7.1

$$N_{evap} = 0.1 \cdot [NO3]_{ly} \cdot (E_{(soil,ly)}'')/[SW]_{ly}$$

Defining the terms:

N_{evap} is the amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha), $NO3_{ly}$ is the nitrate content of the first soil layer (kg N/ha) $E_{(soil,ly)}''$ is the amount of water removed from the first soil layer as a results of evaporation (mm H_2O), and SW_{ly} is the soil water content of the first soil layer (mm H_2O).

Evaluation:

1) Determines the amount of nitrate moving from the first soil layer to the soil surface zone (top 10 mm).

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) EnSym provides evaporation data, soil water content may be able to be determined from soil properties and rainfall additions and evaporation data. Nitrate content of soil by depth data is available in BioSym but not for each soil layer, and equation 3:1.1.1 must still be checked for validity in the Australian context.

3:1.8 Leaching

Equation: No equations are specified in this section as the algorithms used in SWAT to calculate nitrate leaching are solved simultaneously for loss of nitrate in surface runoff and lateral flow equations (see review of chapter 4:2).

3:1.9 Nitrate in the shallow aquifer

Equation 3:1.9.1

$$NO3_{rchrg,i} = \left(1 - exp\left[-1/\delta_{gw}\right]\right) \cdot NO3_{perc} + exp\left[-1/\delta_{gw}\right] \cdot NO3_{rchrg,i-1}$$

Defining the terms:

$NO3_{rchrg,I}$ is the amount of nitrate in recharge entering the aquifers on day *i* (kg N/ha), δ_{gw} is the delay time or drainage time of the overlying geological formations (days), $NO3_{perc}$ is the total amount of nitrate exiting the bottom of the soil profile on day *i* (kg N/ha) (see chapter 4:2 for equation), and $NO3_{rechrg,i-1}$ is the amount of nitrate in recharge entering the aquifers on day *i*-1 (mm H_2O).

Evaluation:

1) Determines the amount of nitrate in recharge entering the shallow and deep aquifers on a given day. A time delay component has been included in the recharge model to allow for the time delay in aquifer recharge

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) EnSym can provide data on recharge and drainage for each hectare of the catchment, however data pertaining to nitrate existing in the soil profile is available in BioSym to a limited capacity. Nitrate data is only available for top and a sub soil, this data is not sufficient.

Equation 3:1.9.2

$$NO3_{sh,i} = (NO3_{sh,i-1} + NO3_{rchrg,i}) \cdot {aq_{sh,i}}/{(aq_{sh,i} + Q_{gw} + w_{revap} + w_{rchrg,dp})}$$

Defining the terms:

$NO3_{sh,I}$ is the amount of nitrate in the shallow aquifer at the end of day *i* (kg N/ha), $NO_{sh,i-1}$ is the amount of nitrate in the shallow aquifer at the end of day *i*-1 (kg N/ha), $NO3_{rchrg,i}$ is the amount of nitrate in recharge entering the aquifer on day *i* (kg N/ha), $NO3_{gw}$ is the amount of nitrate in recharge entering flow from the shallow aquifer on day *i* (kg N/ha), $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day *i* (mm H_2O), Q_{gw} is the groundwater flow or base flow, into the main channel on day *i* (mm H_2O), W_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day *i* (mm H_2O), and $w_{rchrg,dp}$ is the amount of recharge entering the deep aquifer on *i* (mm H_2O).

Evaluation:

1) Determines the amount of nitrate in the shallow aquifer on a given day after processes such as movement of nitrate with recharge to the deep aquifer, movement with groundwater flow into the main channel, transported nitrate out of the aquifer with moving water in response to water deficiencies. This equation takes all of the possible movements of nitrate into account to determine the amount that will be remaining in the shallow aquifer.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) EnSym can only provide data for rainfall, subsurface lateral flows, recharge, and drainage. Groundwater data is currently unavailable. No data is available on nitrate in soil water.

Equation 3:1.9.3

$$NO3_{gw} = (NO3_{sh,i-1} + NO3_{rchrg,i}) \cdot {Q_{gw}}/{(aq_{sh,i} + Q_{gw} + w_{revap} + w_{rchrg,dp})}$$

Defining the terms:

NO_{gw} is the amount of nitrate in groundwater flow from the shallow aquifer on day day *i* (kg N/ha), $NO_{sh,i-1}$ is the amount of nitrate in the shallow aquifer at the end of day *i*-1 (kg N/ha), $NO3_{rchrg,i}$ is the amount of nitrate in recharge entering the aquifer on day *i* (kg N/ha), Q_{gw} is the groundwater flow or base flow, into the main channel on day *i* (mm H_2O), $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day *i* (mm H_2O), W_{revap} is the amount of water moving into

the soil zone in response to water deficiencies on day i (mm H_2O), and $w_{rchrg,dp}$ is the amount of recharge entering the deep aquifer on i (mm H_2O).

Evaluation:

1) Determines the amount of nitrate lost in groundwater flow.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) EnSym can only provide data for rainfall, subsurface lateral flows, recharge, and drainage. Groundwater data is currently unavailable. No data is available on nitrate in soil water.

Equation 3:1.9.4

$$NO3_{revap} = (NO3_{sh,i-1} + NO3_{rchrg,i}) \cdot {w_{revap}}/{(aq_{sh,i} + Q_{gw} + w_{revap} + w_{rchrg,dp})}$$

Defining the terms:

$NO3_{revap}$ is the amount of nitrate in revap to the soil profile from the shallow aquifer on day day i (kg N/ha), $NO_{sh,i-1}$ is the amount of nitrate in the shallow aquifer at the end of day i-1 (kg N/ha), $NO3_{rchrg,i}$ is the amount of nitrate in recharge entering the aquifer on day i (kg N/ha), W_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O), $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm H_2O), Q_{gw} is the groundwater flow or base flow, into the main channel on day i (mm H_2O), and $w_{rchrg,dp}$ is the amount of recharge entering the deep aquifer on i (mm H_2O).

Evaluation:

1) Determines the amount of nitrate lost in revap to the soil profile.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) EnSym can only provide data for rainfall, subsurface lateral flows, recharge, and drainage. Groundwater data is currently unavailable. No data is available on nitrate in soil water.

Equation 3:1.9.5

$$NO3_{dp} = (NO3_{sh,i-1} + NO3_{rchrg,i}) \cdot {w_{rchrg,dp}} / (aq_{sh,i} + Q_{gw} + w_{revap} + w_{rchrg,dp})$$

Defining the terms:

$NO3_{dp}$ is the amount of nitrate in recharge entering the deep aquifer on day day i (kg N/ha), $NO_{sh,i-1}$ is the amount of nitrate in the shallow aquifer at the end of day i-1 (kg N/ha), $NO3_{rchrg,i}$ is the amount of nitrate in recharge entering the aquifer on day i (kg N/ha), $w_{rchrg,dp}$ is the amount of recharge entering the deep aquifer on i (mm H_2O), $aq_{sh,I}$ is the amount of water stored in the shallow aquifer on day i (mm H_2O), Q_{gw} is the groundwater flow or base flow, into the main channel on day i (mm H_2O), and W_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O).

Evaluation:

1) Determines the amount of nitrate transported to the deep aquifer.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) EnSym can only provide data for rainfall, subsurface lateral flows, recharge, and drainage. Groundwater data is currently unavailable. No data is available on nitrate in soil water.

Equation 3:1.9.6

$$NO3_{sh,i} = NO3_{sh,o} \cdot exp[-k_{NO3,sh} \cdot t]$$

Defining the terms:

$NO3_{sh,i}$ is the amount of nitrate in the shallow aquifer at time t (kg N/ha), $NO3_{sh,o}$ is the initial amount of nitrate in the shallow aquifer (kg N/ha), $k_{NO3,sh}$ is the rate constant for removal of nitrate in the shallow aquifer (1/day), and t is the time elapsed since the initial nitrate amount was determined (days).

Evaluation:

1) Determines the amount of nitrate removal in the shallow aquifer, used to account for the net effects of all reaction occurring in the aquifer (biological and chemical).
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) Data for nitrate in soil is available in a limited form in BioSym and soil water is not readily available.

Equation 3:1.9.6

$$t_{\frac{1}{2},NO3,sh} = \frac{0.693}{k_{NO3,sh}}$$

Defining the terms:

$t_{1/2,NO3,sh}$ is the half-life of nitrate in the shallow aquifer (days)

Evaluation:

1) Determines how the rate constant is related to the half-life of nitrate

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian soils.

3) Need to check if the constant values used in the equation are suitable for Australian soils.

4) Data for nitrate in soil is available in a limited form in BioSym and soil water is not readily available

Evaluation of equations within SWAT2005

The following section will evaluate the biological validity of the equations found within the SWAT2005 model that are important and applicable to terrestrial nutrient cycling.

For each equation the following will be outlined:

1) What are the capabilities of the equation?
2) Is the equation appropriate for the Australian landscape?
3) Are specific concepts important in an Australian context not included or accounted for by the equation?
4) Is the input data required for the equation readily available?

Section 3 Chapter 2 Equations: Phosphorus

3:2.1.1 Initialization of soil phosphorus levels

Equation 3:2.1.1

$$minP_{act,ly} = P_{solution,ly} \cdot \frac{1 - pai}{pai}$$

Defining the terms:

$minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg), $P_{solution,ly}$ is the amount of phosphorus in solution (mg/kg), and *pai* is the phosphorus variability index.

Evaluation:

1) Initializes the concentration of phosphorus in the active mineral pool.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) Data not readily available in EnSym

Equation 3:2.1.2

$$minP_{sta,ly} = 4 \cdot minP_{act,ly}$$

Defining the terms:

$minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (mg/kg), and $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg).

Evaluation:

1) Initializes the concentration of phosphorus in the stable mineral pool.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) Data not readily available in EnSym

Equation 3:2.1.3

$$orgP_{hum,ly} = 0.125 \cdot orgN_{hum,ly}$$

Defining the terms:

$orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (mg/kg) and $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg) (equation 3:1.1.2).

Evaluation:

1) Determines the concentration of humic organic phosphorus in a soil layer.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) Given that equation 3:1.1.2 can be solved using carbon data from Ensym, this equation can be solved.

Equation 3:2.1.4

$$orgP_{frsh,surf} = 0.0003 \cdot rsd_{surf}$$

Defining the terms:

$orgP_{frsh,surf}$ is the phosphorus in the fresh organic pool in the top 10 mm (kg P/ha), and rsd_{surf} is material in the residue pool for the top 10 mm of soil (kg/ha).

Evaluation:

1) Determines the amount of phosphorus in the fresh organic pool in the top 10 mm (kg P/ha), set to 0.03% of the initial amount of residue on the soil surface.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent, providing the assumed P:residue ratio is correct for Australian soils.

4) Data on the material in the residue pool is not readily available.

Equation 3:2.1.5

$$\frac{conc_p \cdot \rho_b \cdot depth_{ly}}{100} = \frac{kg\ P}{ha}$$

Defining the terms:

$conc_p$ is the concentration of phosphorus in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm).

Evaluation:

1) Although SWAT allows nutrient levels to be entered as concentrations, this equation is used to convert a concentration to a mass, as SWAT performs all calculations on a mass basis.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) N/A

3:2.2 Mineralization & decomposition/immobilization

Equation 3:2.2.1

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + exp[9.93 - 0.312 \cdot T_{soil,ly}]} + 0.1$$

Defining the terms:

$\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, $T_{soil,ly}$ is the temperature of layer *ly* (ºC).

Evaluation:

1) Determines the nutrient cycling temperature factor for the soil layer. This equation is used within the mineralization and decomposition equations to account for the impact of temperature on these processes.

2) Based on this review, the equation appears suitable for use with Australian soils

3) Constants must be validated before use in Australia.

4) Soil temperature data not readily available

Equation 3:2.2.2

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}}$$

Defining the terms:

$\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*, SW_{ly} is the water content of layer *ly* on a given day (mm H_2O), and FC_{ly} is the water content of layer *ly* at field capacity (mm H_2O).

Evaluation:

1) Determines the nutrient cycling water factor for a soil layer. The nutrient cycling water factor is not allowed to fall below 0.05.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) EnSym can only provide data on rainfall average data (taken from daily time step input data), and evaporation data (actual and pan). BioSym can provide soil water field capacity and calculates soil water on a daily basis. SILO also provides precipitation data.

Equation 3:2.2.3

$$orgP_{act,ly} = orgP_{hum,ly} \cdot \frac{orgN_{act,ly}}{orgN_{act,ly} + orgN_{sta,ly}}$$

Defining the terms:

$orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha), $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (kg P/ha) (equation 3:1.1.2), $orgN_{act,ly}$ is the amount of nitrogen in the active pool (kg N/ha) (equation 3:1.1.3), $orgN_{sta,ly}$ is the amount of nitrogen in the stable pool (kg N/ha) (equation 3:1.1.4).

Evaluation:

1) Determines the amount of phosphorus is present in the active organic pool (kg P/ha), as part of phosphorus in the humus fraction.

2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.

3) Based on this review, no terms were identified as absent.

4) Given that $orgP_{hum,ly}$ can be solved using equation 3:1.1.2 using carbon data from Ensym, this equation can be solved.

Equation 3:2.2.4

$$orgP_{sta,ly} = orgP_{hum,ly} \cdot \frac{orgN_{sta,ly}}{orgN_{act,ly} + orgN_{sta,ly}}$$

Defining the terms:

$orgP_{sta,ly}$ is the amount of phosphorus in the stable organic pool (kg P/ha), $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (kg P/ha), $orgN_{sta,ly}$ is the amount of nitrogen in the stable pool (kg N/ha) (equation 3:1.1.4), $orgN_{act,ly}$ is the amount of nitrogen in the active pool (kg N/ha) (equation 3:1.1.3).

Evaluation:

1) Determines the amount of phosphorus is present in the stable organic pool (kg P/ha), as part of phosphorus in the humus fraction.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.
4) As equations 3:1.1.3 and 3:1.1.4 can be solved, data is available.

Equation 3:2.2.5

$$P_{mina,ly} - 1.4 \cdot \beta_{min} \cdot (\gamma_{tmp,ly} \cdot \gamma_{sw,ly})^{\frac{1}{2}} \cdot orgP_{act,ly}$$

Defining the terms:

$P_{mina,ly}$ is the phosphorus mineralized from the humus active organic P pool (kg P/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly* (equation 3:2.2.1), $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* (equation 3:2.2.2,and $orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha) (equation 3:2.2.3).

Evaluation:

1) Calculates the mineralization from the humus active organic P pool. Phosphorus mineralized from the humus active organic pool is added to the solution P pool in the layer.
2) Based on this review, the equation contains relevant terms and can be applied and generalised for Australian use.
3) Based on this review, no terms were identified as absent.

4) Given that the equations within this equation can be solved with data from EnSym, data is available.

Equation 3:2.2.6

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}}$$

Defining the terms:

$\varepsilon_{C:N}$ is the C:N ration of the residue in the soil layer, rsd_{ly} is the residue in the layer *ly* (kg /ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer *ly* (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer *ly* (kg N/ha).

Evaluation:

1) Determines the C:N ratio of the residue for the soil layer. This equation is used to calculate the decay rate constant which controls decomposition and mineralization processes of the fresh organic phosphorus pool in the first soil layer

2) This equation is suitable for use in Australian soils, providing that the C residue fraction value is accurate. Although no reference has been made, 0.58 is the van Bemmelen conversion factor used to determine the soil organic carbon content of organic material. Whilst not being a precise value, we have found no evidence to suggest that it cannot be employed with reasonable accuracy.

3) Need to verify if 0.58 is the correct fraction of residue that is carbon for Australian soils.

4) EnSym does not supply data on the nitrogen status of the soils or the residue in the soil layer.

Equation 3:2.2.7

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}}$$

Defining the terms:

$\varepsilon_{C:P}$ is the C:P ration of the residue in the soil layer, rsd_{ly} is the residue in the layer *ly* (kg /ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg N/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in layer *ly* (kg N/ha).

Evaluation:

1) Determines the C:P ratio of the residue for the soil layer. This equation is used to calculate the decay rate constant which controls decomposition and mineralization processes of the fresh organic phosphorus pool in the first soil layer

2) This equation is suitable for use in Australian soils, providing that the C residue fraction value is accurate. Although no reference has been made, 0.58 is the van Bemmelen conversion factor used to determine the soil organic carbon content of organic material. Whilst not being a precise value, we have found no evidence to suggest that it cannot be employed with reasonable accuracy.

3) Need to verify if 0.58 is the correct fraction of residue that is carbon for Australian soils.

4) EnSym does not supply data on the phosphorus status of the soils or the residue in the soil layer; however SWAT will automatically set solution phosphorus in all layers to 5 mg/kg soil when concentrations are not independently provided. The validity of this approach needs to be tested.

Equation 3:2.2.8

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot (\gamma_{tmp,ly} \cdot \gamma_{sw,ly})^{\frac{1}{2}}$$

Defining the terms:

$\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly* (equation 3:2.2.1), and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* (equation 3:2.2.2).

Evaluation:

1) This equation is used to determine the decay rate constant, which defines the fraction of residue that is decomposed.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) The applicability of the constants used in this equation must be verified.

4) Soil temperature data is not available to determine $\gamma_{tmp,ly}$ (equation 3:2.2.1), data is available in EnSym to determine $\gamma_{sw,ly}$ (equation 3:2.2.2).

Equation 3:2.2.9

$$\gamma_{ntr,ly} = \min \begin{cases} \exp\left[-0.693 \cdot \frac{(\varepsilon_{C:N} - 25)}{25}\right] \\ \exp\left[-0.693 \cdot \frac{(\varepsilon_{C:P} - 200)}{200}\right] \\ 1.0 \end{cases}$$

Defining the terms:

$\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\varepsilon_{C:P}$ is the C:P ration of the residue in the soil layer, $\varepsilon_{C:N}$ is the C:N ration of the residue in the soil layer.

Evaluation:

1) Determines the nutrient cycling residue composition factor.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) The applicability of the constants used in this equation must be verified.

4) Requires equations 3:2.2.6 and 3:2.2.7, which are suitable for use in Australian soils, providing that the C residue fraction value is accurate. Although no reference has been made, 0.58 is the van Bemmelen conversion factor used to determine the soil organic carbon content of organic material. Whilst not being a precise value, it can be employed with reasonable accuracy. EnSym does not supply data on the phosphorus status of the soils or the residue in the soil layer; however SWAT will automatically set solution phosphorus in all layers to 5 mg/kg soil when concentrations are not independently provided.

Equation 3:2.2.10

$$P_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly}$$

Defining the terms:

$P_{minf,ly}$ is the phosphorus mineralized from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic P pool in layer *ly* (kg P/ha).

Evaluation:

1) Calculates the mineralization from the residue fresh organic P pool (kg P/ha).

2) This equation is suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) The applicability of the constants used in this equation must be verified.

4) Requires the residue decay rate constant $\delta_{ntr,ly}$ (equation 3:2.2.8) for which soil temperature data is not available to determine $\gamma_{tmp,ly}$ (equation 3:2.2.1), data is available in EnSym to determine $\gamma_{sw,ly}$ (equation 3:2.2.2). EnSym does not supply data on the phosphorus status of the soils or the residue in the soil layer; however SWAT will automatically set solution phosphorus in all layers to 5 mg/kg soil when concentrations are not independently provided.

Equation 3:2.2.11

$$P_{dec,ly} = 0.2 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly}$$

Defining the terms:

$P_{dec,ly}$ is the phosphorus decomposed from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic P pool in layer *ly* (kg P/ha).

Evaluation:

1) Calculates the decomposition from the residue fresh organic P pool.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) The applicability of the constants used in this equation must be verified.

4) Requires the residue decay rate constant $\delta_{ntr,ly}$ (equation 3:2.2.8) for which soil temperature data is not available to determine $\gamma_{tmp,ly}$ (equation 3:2.2.1), data is available in EnSym to determine $\gamma_{sw,ly}$ (equation 3:2.2.2). EnSym does not supply data on the phosphorus status of the soils or the residue in the soil layer; however SWAT will automatically set solution phosphorus in all layers to 5 mg/kg soil when concentrations are not independently provided.

<u>3:2.2 Sorption of inorganic P</u>

Equation 3:2.3.1

$$pai = \frac{P_{solution,f} - P_{solution,i}}{fert_{minP}}$$

Defining the terms:

pai is the phosphorus availability index, $P_{solution,f}$ is the amount of phosphorus in solution after fertilizer and incubation, $P_{solution,I}$ is the amount of phosphorus in solution before fertilization, and $fert_{minP}$ is the amount of soluble P fertilizer added to the sample.

Evaluation:

1) Determines the P availability index
2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.
3) No terms were identified as absent from this equation during this review.
4) Data is not readily available to utilise this equation

Equation 3:2.3.2

$$P_{(sol|act,ly)} = P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1 - pai}\right)$$

$$\text{if } P_{solution,ly} > minP_{act,ly} \cdot \left(\frac{pai}{1 - pai}\right)$$

Defining the terms:

$P_{(sol|act,ly)}$ is the amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha), $P_{solution,ly}$ is the amount of phosphorus in solution (kg P/ha), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and pai is the phosphorus availability index.

Evaluation:

1) In conjunction with equation 3:2.3.3, this equilibrium governs the movement of phosphorus between the solution and active mineral pools.
2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.
3) No terms were identified as absent from this equation during this review.
4) Data is not readily available to utilise this equation and the equations held within this equation: $minP_{act,ly}$ (3:2.1.1) and pai (3:2.3.1).

Equation 3:2.3.3

$$P_{(sol|act,ly)} = 0.1 \cdot \left(P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1 - pai}\right)\right)$$

if $P_{solution,ly} < minP_{act,ly} \cdot \left(\frac{pai}{1 - pai}\right)$

Defining the terms:

$P_{(sol|act,ly)}$ is the amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha), $P_{solution,ly}$ is the amount of phosphorus in solution (kg P/ha), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and *pai* is the phosphorus availability index.

Evaluation:

1) In conjunction with equation 3:2.3.2, this equilibrium governs the movement of phosphorus between the solution and active mineral pools.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) Based on this review, no terms were identified as absent, however the constant for conversion must be verified for Australian soils and the transfer of phosphorus between the soluble and active mineral pool.

4) Data is not readily available to utilise this equation and the equations held within this equation: $minP_{act,ly}$ (3:2.1.1) and *pai* (3:2.3.1).

Equation 3:2.3.4

$$P_{(act|sta,ly)} = \beta_{eqP} \cdot (4 \cdot minP_{act,ly} - minP_{sta,ly})$$

if $minP_{sta,ly} < 4 \cdot minP_{act,ly}$

Defining the terms:

$P_{(act|sta,ly)}$ is the amount of phosphorus transferred between the active and stable mineral pools (kg P/ha), β_{eqP} is the slow equilibration rate constant (0.0006 d^{-1}), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (kg P/ha).

Evaluation:

1) When not in equilibrium the movement of phosphorus between the active and stable mineral pools is governed by equation 3:2.3.4 in conjunction with equation 3:2.3.5.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) No terms were identified as absent from the equation during this review; however the constants must be verified for Australian.

4) Data is not readily available in EnSym to utilise this equation and the equations held within this equation: $minP_{act,ly}$ (3:2.1.1), and $minP_{sta,ly}$ (3:2.1.2).

Equation 3:2.3.5

$$P_{(act|sta,ly)} = 0.1 \cdot \beta_{eqP} \cdot (4 \cdot minP_{act,ly} - minP_{sta,ly})$$

$$\text{if } minP_{sta,ly} > 4 \cdot minP_{act,ly}$$

Defining the terms:

$P_{(act|sta,ly)}$ is the amount of phosphorus transferred between the active and stable mineral pools (kg P/ha), β_{eqP} is the slow equilibration rate constant (0.0006 d^{-1}), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (kg P/ha).

Evaluation:

1) When not in equilibrium the movement of phosphorus between the active and stable mineral pools is governed by equation 3:2.3.4 in conjunction with equation 3:2.3.5.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) No terms were identified as absent during this review; however the constant must be verified for Australian. Data is not readily available to utilise this equation and the equations held within this equation: $minP_{act,ly}$ (3:2.1.1), and $minP_{sta,ly}$ (3:2.1.2).

4) Data is not readily available in EnSym to utilise this equation and the equations held within this equation: $minP_{act,ly}$ (3:2.1.1), and $minP_{sta,ly}$ (3:2.1.2).

3:2.4 Leaching

Equation 3:2.4.1

$$P_{perc} = \frac{P_{solution,surf} \cdot w_{perc,surf}}{10 \cdot \rho_b \cdot depth_{surf} \cdot k_{d,perc}}$$

Defining the terms:

P_{perc} is the amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), $w_{perc,surf}$ is the amount of water percolating into the first soil layer from the top 10 mm on

a given day (mm H_2O), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equal to the bulk density of the first soil layer), $depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,perc}$ is the phosphorus percolation coefficient (10 m^3/Mg). The phosphorus percolation coefficient is the ratio of the phosphorus concentration in the surface 10 mm of soil to the concentration of phosphorus in percolate.

Evaluation:

1) Determines the amount of solution P moving from the top 10 mm into the first soil layer. SWAT allows soluble P to leach only from the top 10 mm of the soil into the first layer. This is limiting, as it does not fully model the movement of P through the soil layers, and only accounts for the movement from the top 10 mm.

2) Based on this review, the equation appears suitable for use in Australian soils, providing that the constants used are appropriate for Australian soils.

3) Based on this review, no terms were identified as absent from the equation.

4) EnSym does not provide data for phosphorus solution content. Bulk density data is not available depending on the extent of the soil profile data stored with the appropriate soil codes used for classification in EnSym. Soil depth data is not available in EnSym.

<u>3:2.5 Phosphorus in the shallow aquifer</u>

No equations are provided in this section as SWAT2005 does not directly model the soluble phosphorus pool in the shallow aquifer. Rather than provide an equation to model phosphorus in the shallow aquifer, SWAT2005 allows the user to specify the phosphorus loadings in the groundwater and shallow aquifer, however this concentration of soluble phosphorus is assumed to be constant throughout the simulation.

SECTION 4 CHAPTER 2 NUTRIENT TRANSPORT

4:2.1 Nitrate movement

Equation 4:2.1.2

$$conc_{NO3,mobile} = \frac{NO3_{ly} \cdot \left(1 - exp\left[\frac{-w_{mobile}}{(1-\theta_e) \cdot SAT_{ly}}\right]\right)}{w_{mobile}}$$

Defining the terms:

$conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water in a given layer (kg N/mm H_2O), $NO3_{ly}$ is the amount of nitrate in the layer (kg N/ha), w_{mobile} is the amount of mobile water in the layer (mm H_2O), θ_e is the fraction of porosity from which anions are excluded, and SAT_{ly} is the saturated water content of the soil layer (mm H_2O).

Evaluation:

1) Determines the concentration of nitrate in the mobile water fraction. The equation uses concentrations of nitrate in the mobile water in conjunction with the volume of water moving in each pathway, this enables the user to obtain a value that represents the mass of nitrate lost from the soil layer during water movement between and within pathways (surface runoff, lateral flow, or percolation).

2) Based on this review, the equation appears suitable for use with Australian soils

3) Constants used in this equation must be verified prior to use in an Australian context.

4) Data not readily available in EnSym. Water data is available in BioSym. Data for the initial nitrate concentrations of a layer is unavailable.

Equation 4:2.1.3

$$w_{mobile} = Q_{surf} + Q_{lat,ly} + w_{perc,ly} \quad \textbf{for the top 10 mm}$$

Defining the terms:

w_{mobile} is the amount of mobile water in the layer (mm H_2O), Q_{surf} is the surface runoff generated on a given day (mm H_2O), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O), $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Evaluation:

1) Determines the amount of mobile water in the layer for the top 10 mm of soil. The amount of mobile water is the amount of water lost by surface runoff, lateral flow or percolation.

2) Based on this review, the equation appears suitable for use with Australian soils, as it is a general formula based on simple concepts of soil water movement and can be generalised to any landscape

3) No terms were identified as absent from the equation during this review.

4) EnSym provides data for surface runoff, sub-surface later flows, recharge, rainfall, and transpiration. This data should enable the equation to be utilised. The BioSym file contains data on infiltration rates and bulk density of soil types, enabling the determination of water percolation to underlying soil layers.

Equation 4:2.1.4

$$w_{mobile} = Q_{lat,ly} + w_{perc,ly} \quad \textbf{for lower soil layers}$$

Defining the terms:

w_{mobile} is the amount of mobile water in the layer (mm H_2O), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Evaluation:

1) Determines the amount of mobile water in the layer for the lower soil layers. The amount of mobile water is the amount of water lost by surface runoff, lateral flow or percolation.

2) Based on this review, the equation appears suitable for use with Australian soils, as it is a general formula based on simple concepts of soil water movement and can be generalised to any landscape

3) No terms were identified as absent from the equation during this review.

4) EnSym provides data for surface runoff, sub-surface later flows, recharge, rainfall, and transpiration. This data should enable the equation to be utilised. The BioSym file contains data on infiltration rates and bulk density of soil types, enabling the determination of water percolation to underlying soil layers.

Equation 4:2.1.5

$$NO3_{surf} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{surf}$$

Defining the terms:

$NO3_{surf}$ is the nitrate removed in surface runoff (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the top 10 mm of soil (kg N/mm H_2O), and Q_{surf} is the surface runoff generated on a given day (mm H_2O).

Evaluation:

1) Determines the amount of nitrate removed in surface runoff. SWAT limits the interaction of surface runoff and transport of nutrients in the top 10 mm of soil. The nitrate percolation coefficient allows the user to set the concentration of nitrate in surface runoff to a fraction of the concentration in percolate.

2) Based on this review, the equation appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review. The nitrate percolation coefficient must be validated for Australian use.

4) EnSym provides data for surface runoff. Data for nitrate concentration in mobile water is not available (equation 4:2.1.2), whilst BioSym provides the nitrate percolation coefficient.

Equation 4:2.1.6

$$NO3_{lat,ly} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{lat,ly} \text{ for the top 10 mm}$$

Defining the terms:

$NO3_{lat,ly}$ is the nitrate removed in lateral flow from a layer (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the top 10 mm of soil (kg N/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O).

Evaluation:

1) Calculates the nitrate removed in lateral flow for the top 10 mm of soil. The nitrate percolation coefficient allows the user to set the concentration of nitrate in surface runoff to a fraction of the concentration in percolate.

2) Based on this review, the equation appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review. The nitrate percolation coefficient must be validated for Australian use.

4) EnSym provides data for surface runoff and subsurface lateral flows of water. Data for nitrate concentration in mobile water is not available (equation 4:2.1.2), BioSym provides

the nitrate percolation coefficient. Discharge could potentially be estimated using drainage, rainfall and subsurface flow data found in EnSym.

Equation 4:2.1.7

$NO3_{lat,ly} = conc_{NO3,mobile} \cdot Q_{lat,ly}$ **for lower soil layers**

Defining the terms:

$NO3_{lat,ly}$ is the nitrate removed in lateral flow from a layer (kg N/ha), $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the soil layer (kg N/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O).

Evaluation:

1) Calculates the nitrate removed in lateral flow for lower layers of soil.

2) Based on this review, the equation appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review.

4) EnSym provides data for surface runoff and subsurface lateral flows of water. Data for nitrate concentration in mobile water is not available (equation 4:2.1.2), and discharge could potentially be estimated using drainage, rainfall and subsurface flow data found in EnSym.

Equation 4:2.1.8

$NO3_{perc,ly} = conc_{NO3,mobile} \cdot w_{perc,ly}$

Defining the terms:

$NO3_{perc,ly}$ is the nitrate moved to the underlying layer by percolation (kg N/ha), $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the layer (kg N/mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Evaluation:

1) Determines the nitrate moved to the underlying layer of soil by percolation (kg N/ha).

2) Based on this review, the equation is appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review.

4) EnSym provides data for surface runoff and subsurface lateral flows of water. Data for nitrate concentration in mobile water is not available (equation 4:2.1.2), and percolation could potentially be estimated using drainage, rainfall and subsurface flow data found in EnSym.

4:2.2 Organic N in surface runoff

Equation 4:2.2.1

$$orgN_{surf} = 0.001 \cdot conc_{orgN} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{N:sed}$$

Defining the terms:

$orgN_{surf}$ is the amount of organic nitrogen transported to the main channel in surface runoff (kg N/ha), $conc_{orgN}$ is the concentration of organic nitrogen in the top 10 mm (g N/ metric ton soil), *sed* is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{N:sed}$ is the nitrogen enrichment ratio.

Evaluation:

1) Determines the amount of organic nitrogen transported to the main channel in surface runoff (kg N/ha). This equation is used to help determine the nitrogen loadings in sediment in the HRU.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review. However, the constant must be validation for Australian soils.

4) Data is not available for the organic nitrogen content of soils or the nitrogen enrichment ratio. Sediment yield may be determined using data available in EnSym.

Equation 4:2.2.2

$$conc_{orgN} = 100 \cdot \frac{orgN_{frsh,surf} + orgN_{sta,surf} + orgN_{act,surf}}{\rho_b \cdot depth_{surf}}$$

Defining the terms:

$conc_{orgN}$ is the concentration of organic nitrogen in the soil surface layer, $orgN_{frsh,surf}$ is the nitrogen in the fresh organic pool in the top 10 mm (kg N/ha) (equation 3:1.1.5), $orgN_{sta,surf}$ is the nitrogen in the stable organic pool (kg N/ha) (equation 3:1.1.4), $orgN_{act,surf}$ is the nitrogen in the active organic pool in the top 10 mm (kg N/ha) (equation 3:1.1.3), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm).

Evalution:

1) Calculates the concentration of organic nitrogen in the soil surface layer. This equation can be used to help solve equation 4:2.2.1.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, and the constant is a mass conversion factor, hence does not need validation.

4) Data is available to solve equation 3:1.1.3, 3:1.1.4, and 3:1.1.5 in EnSym, and soil characterisation data to determine bulk density is available in part in BioSym data.

<u>4:2.2.1 Enrichment ration</u>

Equation 4:2.2.3

$$\varepsilon_{N:sed} = 0.78 \cdot (conc_{sed,surq})^{-0.2468}$$

Defining the terms:

$\varepsilon_{N:sed}$ is the nitrogen enrichment ration for a storm event, $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O).

Evaluation:

1) Calculates the nitrogen enrichment ratio. This equation is used to help solve equation 4:2.2.1.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Surface runoff and erosion data are available in EnSym, however sediment concentration is not available.

Equation 4:2.2.4

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}}$$

Defining the terms:

$conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O), *sed* is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha) and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Evaluation:

1) Determines the concentration of sediment in surface runoff. This equation is required to solve equation 4:2.2.3.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Surface runoff data and area of each HRU is available in EnSym, however sediment yield data does not seem readily available.

4:2.3 Soluble phosphorus movement

Equation 4:2.3.1

$$P_{surf} = \frac{P_{solution} \cdot Q_{surf}}{\rho_b \cdot depth_{surf} \cdot k_{d,surf}}$$

Defining the terms:

P_{surf} is the amount of soluble phosphorus lost in surface runoff (kg P/ha), $P_{solution}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), Q_{surf} is the amount of surface runoff on a given day (mm H_2O), ρ_b is the bulk density of the first soil layer (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer), and $depth_{surf}$ is the depth of the soil "surface" layer (10 mm), and $k_{d,surf}$ is the phosphorus soil partitioning coefficient (m^3/Mg).

Evaluation:

1) Determines the amount of solution P transported in surface runoff. The phosphorus soil partitioning coefficient is the ratio of the soluble phosphorus concentration in the surface 10 mm of soil to the concentration of soluble phosphorus in surface runoff.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review.

4) Data is not available in EnSym or BioSym.

4:2.4 Organic & mineral P attached to sediment in surface runoff

Equation 4:2.4.1

$$sedP_{surf} = 0.001 \cdot conc_{sedP} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{P:sed}$$

Defining the terms:

$sedP_{surf}$ is the amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha), $conc_{sedP}$ is the concentration of phosphorus attached to sediment in the top 10

mm (g P/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{P:sed}$ is the phosphorus enrichment ratio.

Evaluation:

1) Determines the amount of phosphorus transported with sediment to the stream, or main channel in surface runoff.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review.

4) Data is available in BioSym, however these values held within the BioSym database need to be checked for validity.

Equation 4:2.4.2

$$conc_{sedP} = 100 \cdot \frac{(minP_{act,surf} + minP_{sta,surf} + orgP_{hum,surf} + orgP_{frsh,surf})}{\rho_b \cdot depth_{surf}}$$

Defining the terms:

$conc_{sedP}$ is the concentration of phosphorus attached to sediment in the soil surface layer, $minP_{act,surf}$ is the amount of phosphorus in the active mineral pool in the top 10 mm (kg P/ha), $minP_{sta,surf}$ is the amount of phosphorus in the stable mineral pool in the top 10 mm (kg P/ha), $orgP_{hum,surf}$ is the amount of phosphorus in the humic organic pool in the top 10 mm (kg P/ha), $orgP_{frsh,surf}$ is the amount of phosphorus in the fresh organic pool in the top 10 mm (kg P/ha), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm)

Evaluation:

1) Determines the concentration of phosphorus attached to sediment in the soil surface layer, to contribute to the users understanding of phosphorus loading in sediment.

2) Based on this review, the equation is appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review.

4) BioSym appears to contain data soluble P and organic P levels for top and lower surface levels. However, it is unclear if this is current data, and no units are provided. Therefore P data held within BioSym should be checked for validity.

<u>4:2.4.1 Enrichment ratio</u>

Equation 4:2.4.3

$$\varepsilon_{P:sed} = 0.78 \cdot (conc_{sed,surq})^{-0.2468}$$

Defining the terms:

$\varepsilon_{P:sed}$ is the phosphorus enrichment ration for a storm event, $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O).

Evaluation:

1) Calculates the phosphorus enrichment ratio.
2) Based on this review, the equation is appears suitable for use with Australian soils.
3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.
4) Surface runoff and erosion data are available in EnSym, however sediment concentration is not available.

Equation 4:2.4.4

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}}$$

Defining the terms:

$conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O), *sed* is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha) and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Evaluation:

1) Determines the concentration of sediment in surface runoff.
2) Based on this review, the equation is appears suitable for use with Australian soils.
3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.
4) Surface runoff data and area of each HRU is available in EnSym, however sediment yield data does not seem readily available in either BioSym or EnSym.

4:2.5 Nutrient lag in surface runoff and lateral flow

Equation 4:2.5.1

$$NO3_{surf} = \left(NO3'_{surf} + NO3_{surstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right)$$

Defining the terms:

$NO3_{surf}$ is the amount of nitrate discharged to the main channel in surface runoff on a given day (kf N/ha), $NO3'_{surf}$ is the amount of surface runoff nitrate generated in the HRU on a given day (kg N/ha), $NO3_{surstor,i-1}$ is the surface runoff nitrate stored or lagged from the previous day (kg N/ha), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

Evaluation:

1) Determines the amount of nitrate discharged to the main channel in surface runoff on a given day (kg N/ha). This equation is part of a series of equations used to determine the amount of nutrients released to the channel. This is done once the nutrient load in surface runoff and lateral flow is determined.

2) Based on this review, the equation appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Data does not appear readily available in either BioSym or EnSym.

Equation 4:2.5.2

$$NO3_{lat} = \left(NO3'_{lat} + NO3_{latstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-1}{TT_{lag}}\right]\right)$$

Defining the terms:

$NO3_{lat}$ is the amount of nitrate discharged to the main channel in lateral flow on a given day (kg N/ha), $NO3'_{lat}$ is the amount of lateral flow nitrate generated in the HRU on a given day (kg N/ha), $NO3_{latstor,i-1}$ is the lateral flow nitrate stored of lagged from the previous day (kg N/ha), TT_{lag} is the lateral flow travel time (days).

Evaluation:

1) Determines the amount of nitrate discharged to the main channel in lateral flow on a given day (kg N/ha). This equation is part of a series of equations used to determine the amount of nutrients released to the channel. This is done once the nutrient load in surface runoff and lateral flow is determined.

2) Based on this review, the equation appears suitable for use with Australian soils

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Data does not appear readily available in either BioSym or EnSym.

Equation 4:2.5.3

$$orgN_{surf} = \left(orgN'_{surf} + orgN_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right)$$

Defining the terms:

$orgN_{surf}$ is the amount of organic N discharged to the main channel in surface runoff on a given day (kg N/ha), $orgN'_{surf}$ is the organic N loading generated in the HRU on a given day (kg N/ha), $orgN_{stor,i-1}$ is the organic N stored or lagged from the previous day (kg N/ha), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

Evaluation:

1) Determines the amount of organic N discharged to the main channel in surface runoff on a given day (kg N/ha). This equation is part of a series of equations used to determine the amount of nutrients released to the channel. This is done once the nutrient load in surface runoff and lateral flow is determined.

2) Based on this review, the equation appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Data does not appear readily available in either BioSym or EnSym.

Equation 4:2.5.4

$$P_{surf} = \left(P'_{surf} + P_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right)$$

Defining the terms:

P_{surf} is the amount of solution P discharged to the main channel in surface runoff on a given day (kg P/ha), P'_{surf} is the amount of solution P loading generated in the HRU on a given day (kg P/ha), $P_{stor,i-1}$ is the solution P stored or lagged from the previous day (kg N/ha), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

Evaluation:

1) Determines the amount of solution P discharged to the main channel in surface runoff on a given day (kg N/ha). This equation is part of a series of equations used to determine the amount of nutrients released to the channel. This is done once the nutrient load in surface runoff and lateral flow is determined.

2) Based on this review, the equation appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Data does not appear readily available in either BioSym or EnSym.

Equation 4:2.5.5

$$sedP_{surf} = \left(sedP'_{surf} + sedP_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right)$$

Defining the terms:

$sedP_{surf}$ is the amount of sediment-attached P discharged to the main channel in surface runoff on a given day (kg P/ha), $sedP'_{surf}$ is the amount of sediment-attached P loading generated in the HRU on a given day (kg P/ha), $sedP_{stor,i-1}$ is the sediment-attached P stored or lagged from the previous day (kg N/ha), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

Evaluation:

1) Determines the amount of sediment-attached P discharged to the main channel in surface runoff on a given day (kg N/ha). This equation is part of a series of equations used to determine the amount of nutrients released to the channel. This is done once the nutrient load in surface runoff and lateral flow is determined.

2) Based on this review, the equation appears suitable for use with Australian soils.

3) No terms were identified as absent from the equation during this review, however the constants used in this equation need validation for Australian use.

4) Data does not appear readily available in either BioSym or EnSym.

Evaluation of equations within SWAT2005

The following section will evaluate the biological validity of the equations found within the SWAT2005 model that are important and applicable to terrestrial nutrient cycling.

The review of this section will take a conceptual approach to evaluating the biological validity of the components held within this chapter. A review of each equation will not be carried out, rather a brief examination of the concepts used to perform the analyses will be used to evaluate the chapter. Key criteria were identified in conjunction with Mark Eigenramm and Wayne Lewis during the consultation periods with the DSE.

The evaluation will include:

1) How well the modelling concepts can be applied in an Australian context

2) The limitations and advantages of the modelling concept

SECTION 5 CHAPTER 1: GROWTH CYCLE

5:1.1 Heat Units

SWAT2005 employs the heat unit theory, used to regulate the growth cycle of plants. 'The heat unit theory postulates plants have heat requirements that can be quantified and linked to time and maturity ' (Neitsch *et al.*, 2005), which accounts for the well understood concept of temperature governing a plants growth and hence a plants own temperature range for minimum, optimum, and maximum growth. The method assumes that the rate of plant growth is directly proportional to the increase in temperature. This theory can easily be applied in an Australian context, as it takes into account the regional temperature data, and requires detailed data inputs specific to the study region

Limitations: The heat unit theory is unable to account for the harmful impacts of temperatures that exceed a plants range to a detrimental degree, and thus SWAT2005 assumes that all heats above the base temperature accelerate crop growth and development.

Advantageous: A simplistic approach to determining plant growth, that has been used, documented in successfully applied several studies (Neitsch et al., 2005).

5:1.1.1 Heat Unit Scheduling

The heat unit theory and the theory adaptations have been proven as an effective tool for predicting harvest dates and developmental stages for many types of crops

Limitations: Heat unit scheduling for application of fertilizers or pesticides cannot account for the real weather that will occur on specific day, for example, fertilizers are not generally

scheduled for application on a rainy day yet a heat unit fraction that triggers application will occur regardless of the rainfall. The negative impacts of this will be the large amount of applied material transported in surface runoff.

Advantages: Heat unit theory can be used to schedule management operations by day or by fraction of potential heat units. SWAT2005 can perform the operation on the month or day if it has been specified for the timing of the operation, or the model can use the fraction of potential heat units specified if month and day are not specified. This shows that there is some flexibility in the model. Operations are timed as a function of temperature in the scheduling by heat units model component. This is particularly advantageous for simulations in large catchments where there is a significant variation in climate across the catchment.

Data Input Required	Availability	Source
Number of day to reach plant maturity	Limited	BioSym
Day of plant sowing	N/A	N/A
Mean daily temperature (ºC)	✓	EnSym & SILO
Plant's base or minimum temperature for growth	Limited	BioSym

Review: The equations held within this section are both suitable and useful for application in the Australian context. They can be generally applied across different catchments that are subjected to different environmental conditions due to the incorporation of this into the equations. Land use type classifications held within the database files must be checked to ensure that they are comparable to Australian land use classifications.

5:1.2 Dormancy

SWAT2005 assumes that dormancy occurs in trees, perennials and cool season annuals, as the day length nears the shortest day length for the year. It is assumed that during the dormancy period, no plant growth occurs. SWAT2005 calculates the beginning and the end of the dormancy periods, defining it through a day length threshold. Dormancy is considered important as biomass conversion to residue and minimum leaf area index occurs in trees and perennials

Limitations: It is uncertain how well the equations will account for native Australia species, and the differences for example found in Eucalyptus species with dormancy and biomass contribution to residue during dormant periods. It is unclear how well SWAT2005 can account for the evergreen nature of many Australian native species.

Advantages: The equations account for variation in latitude influencing day length and hence dormancy.

Data Input Required	Availability	Source
Minimum daylength for the catchment during the year (hrs)	Limited	BioSym
Plant dormancy threshold (hrs)	Limited	BioSym

Latitude of the sub-basin (degrees)	✓	EnSym
Land cover/plant classification	✓	EnSym &BioSym
Minimum leaf area index for plant during dormant period (m^2/m^2)	Limited	BioSym
Fraction of tree biomass accumulated each year that is converted to residue during dormancy	Limited	BioSym

Review: Based on this review, the equations held within this section appear both suitable and useful for application in the Australian context. Dormancy in Australian native species must be investigated and verified to ensure that the equations are applicable.

5:1.3 Plant Types

SWAT2005 categorises plants into seven different types: warm season annual legume, cold season annual legume, perennial legume, warm season annual, cold season annual, perennials, and trees.

Limitations: The model does not account for differences between native and exotic species. Generalised trees in the northern and southern hemisphere are likely to be different in biological characteristics and requirements.

Advantages: The generality of the categories in SWAT2005 make the model more broadly applicable.

Review: No equations are held in this chapter. However the classification of plant types must be reviewed to ensure that all major crop and native plant types are accounted for in an Australian context (especially the definition of "a tree").

SECTION 5 CHAPTER 2: OPTIMAL GROWTH

Plant growth under ideal growing conditions is simulated as potential plant growth. Ideal conditions for optimal plant growth are defined by SWAT2005 as adequate water and nutrient supply and a favourable climate.

5:2.1 Potential Growth

'Plant growth is modelled by simulating leaf area development, light interception and conversion of intercepted light into biomass assuming a plant species-specific radiation-use efficiency' (Neitsch et al., 2005).

5:2.1.1 Biomass production

This section includes equations that cover important factors to consider when attempting to model potential growth: biomass production, impacts of climate on radiation-use efficiency, and modification of biomass calculation for trees.

Limitations:

Leaf Area index data for different plant types is limited in availability, and accuracy.

Assumes that the threshold vapour pressure deficit for reduced radiation-use efficiency is the same (1.0 kPa) is the same for all plants.

Modifications of biomass calculations for trees only account for fully developed/mature trees. Although a limitation equation has been used to simulate accumulation of biomass under seedlings/saplings, tree growth annual is fixed by age relative to the number of years for the tree to reach full development.

Advantages:

Utilises the well accepted and validated Beer's Law.

SWAT2005 can modify the default radiation-use efficiency values in the plant database for use in climate changes studies.

Review: Based on this review, we consider the equations held within this section biologically valid, meaning that they appropriate equations for the modelling task required and can be applied successfully to an Australian environment, and are derived or taken from well validated sources.

5:2.1.2 Canopy Cover and Height

Review: The equations held within this section enable SWAT2005 to account for the changes and differences in canopy height and leaf area for annuals and perennials through the growing season. Based on this review, we consider the equations to provide a comprehensive analysis of the changes in leaf area index and the relationship this has with heat units (discussed in section 5:1.1). Australian eucalyptus species under drought conditions can drop between 50-97% of pre-drought LAI (Pook, 1985), significantly reducing overall LAI. This is not accounted for in the SWAT model.

5:2.1.3 Root Development

Review: The equations held within this section enable SWAT2005 to calculate root biomass accounting for the differences in root biomass partitioning at emergence and at maturity. Root depth varies according to plant type. For simplicity purposes and wide applicability of the equations SWAT2005 assumes that perennials and trees have roots down to the maximum rooting depth defined for the soil throughout the growing season.

Limitations: The fraction definition by which SWAT defines the root biomass partitioning for emergent and mature plants may not be accurate for all crop species and Australian native species.

Advantages: Accounts for the influence of soil type on maximum rooting depth for a plant.

5:2.1.4 Maturity

Maturity of a plant is defined in SWAT2005 as the point when the fraction of potential heat units accumulated is equal to 1.00. Once maturity is reached it is assumed that water and nutrient uptake is no longer occurring.

Review: Based on this review, we consider this concept suitable for use in simulation for Australian landscapes.

Data Input Required	Availability	Source
Incident total solar (MJ m^{-2})	✓	EnSym or SILO
Light extinction coefficient	Limited	BioSym
Leaf Area Index (LAI)	Limited	BioSym
Radiation-use efficiency of the plant (10^{-1} g/MJ)	?	-
Amount of intercepted photosynthetically active radiation on a given day (MJ m^{-2})	?	-
CO_2 concentration in the atmosphere (ppmv)	?	-
Radiation-use efficiency ofr the plant at vapour deficit pressure of 1 kPa	?	-
Vapour pressure deficit (kPa)	?	-
Threshold vapour pressure deficit (kPa)	?	-
Current age of the tree (years)	Limited	BioSym
No. of years for the tree species to reach maturity	✓	BioSym
Biomass of a fully developed tree stand for the specific tree spp. (metric tons/ha)	✓	BioSym
Beer's Law constant	✓	BioSym
Rate of decline in radiation-use efficiency per unit increase in vapour pressure deficit (kg/ha $\cdot(MJ/m^2)^{-1}\cdot kPa^{-1}$ or (10^{-1} g/MJ)$\cdot kPa^{-1}$)	?	-
Potential heat units for plant growing at beginning of simulation (heat units)	✓	BioSym, EnSym & SILO
Potential heat units for plant whose growth is initiated in a planting operation (heat units)	✓	BioSym, EnSym & SILO
Fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve	?	-
Fraction of the maximum plant leaf area index corresponding to the 1st point on the optimal leaf area development curve	?	-
Fraction of the growing season corresponding to the 2ndt point on the optimal leaf area development curve	?	-
Fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve	?	-
Plant's potential maximum canopy height (m)	?	-
Potential maximum leaf area index for the plant	✓	BioSym
Fraction of growing season at which senescence becomes the dominant growth process	Limited	BioSym
Maximum rooting depth in soil (mm)	✓	BioSym
Maximum rooting depth for plant (mm)	✓	BioSym

5:2.2 Water Uptake by Plants

When modelling water uptake by plants, the amount of water available, the amount of water that can be used by plants, what happens to plants when there is insufficient water available and actual water uptake by plants, are all important factors to consider. SWAT2005 provides a series of equations that addresses each of these factors.

Limitations: No major limitations were identified in this review.

Advantages:

The equations account for the differences in root density with soil depth.

Initial potential water uptake by plants is modified from a given soil layer to reflect soil water availability when 1) the upper soil layers in the profile do not contain enough water to meet calculated plant uptake, SWAT2005 enables the user to use lower soil layers to compensate, hence adjusting the potential water uptake; 2) soil water content decreases and plant efficiency in uptake decreases SWAT2005 enables the modification of potential water uptake to be adjusted to suit drier soils; and 3) with or without modifications prior mentioned, SWAT2005 can calculate the actual water uptake by plants.

Review: The equations held within this chapter addressing water uptake by plants, use simple and widely available data to effectively simulate and model these processes. These equations are not limited to a specific landscape and can be used and generalised to Australian catchments.

Data Inputs Required	Availability	Source
Plant uptake compensation factor	Not available	-
Maximum plant transpiration on a given day (mm H_2O)	Limited	BioSym &EnSym
Depth from soil surface (mm)	Limited	BioSym &EnSym
Depth of root development in the soil (mm)	Limited	BioSym
Potential water uptake for the profile to the lower boundary soil layer (mm H_2O)	?	-
Potential water uptake for the profile to the upper boundary soil layer (mm H_2O)	?	-
Water uptake demand not met by overlying soil layers (mm H_2O)	Not available	-
Water content of a soil layer at wilting point (mm H_2O)	✓	BioSym
Number of soil layers in the soil profike	✓	EnSym
Actual amount of transpiration on a given day	✓	EnSym

5:2.3 Nutrient Uptake by Plants

5:2.3.1 Nitrogen Uptake

SWAT2005 calculates nitrogen in plants as a fraction of nitrogen in plant biomass, as a function of growth stage for the plant given optimal growing conditions.

Limitations:

The equations require a large amount of specific input data, which is limited in availability. Data such as the "normal fraction of nitrogen in plant biomass at maturity" and "normal fraction of nitrogen in plant biomass at emergence" is limited in availability and is constrained to specific crop species that have been extensively researched.

It is unclear how well the equations can account for different plant types and mixed crops or landscapes.

Advantages:

Equations are able to differentiate potential nitrogen uptake for soil layers of different depths, and users are enabled to adjust the nitrogen distribution uptake parameter. This accounts for the differences in root density distribution with soil depth and the proportion of nitrogen uptake that occurs as a result of these differences through the soil profile. The model allows lower soil layers in the root zone to fully compensate for lack of nitrate in the upper layers. The nitrogen uptake distribution parameter also enables the user to account for nitrate loss in surface runoff from the top 10 mm of soil.

Within the equation, the model is able to account for different growth stages of a plant.

Review: The equations held within this section addressing nitrogen content and uptake of nitrogen by plants are simplistic with majority of the data required readily available. The equations appear broadly applicable to Australian landscapes.

5:2.3.1.1 Nitrogen Fixation

Nitrogen fixation is calculated as a function of soil water, soil nitrate content and growth stage of the plant. SWAT enables the plant to obtain additional nitrogen by modelling nitrogen fixation parameters.

Limitations:

Differences in root density for different plant types are not accounted for.

Differences in the efficiency of different plant species in nitrogen fixation are not accounted for in the equations.

Advantages:

Growth stage factor enables the model to reflect the build-up and decline of nitrogen fixing bacteria in the plant roots within changes in season and during growing seasons.

Equations take into consideration the impacts of wetting and drying of soils on nitrate fixation processes.

Review: Based on this review, we consider the equations held within this section addressing nitrogen fixation by plants applicable to Australian landscapes and broadly across plant types. The data required for the equations is readily available in the BioSym and EnSym databases.

Input Data Required	Availability	Source
Normal fraction of nitrogen in plant biomass at maturity	✓	BioSym
Normal fraction of nitrogen in plant biomass at emergence	✓	BioSym
Heat units	✓	BioSym, EnSym & SILO
Optimal fraction of nitrogen in the plant biomass for the current growth stage	Limited	BioSym
Total plant biomass on a given day (kg ha^{-1})	Limited	BioSym
Potential increase in total plant biomass on a given day (kg/ha)	Unknown	-
Depth of root development in the soil (mm)	✓	BioSym
Potential nitrogen uptake for soil layer (kg N/ha)	Unknown	-
Nitrogen demand not met by overlying soil layers (kg N/ha)	Unknown	-
Nitrate content of soil layers (kg NO_{3-} N/ha)	✓	BioSym
Nitrogen uptake distribution parameter	✓	BioSym
Growth stage factor (0.0-1.0)	✓	BioSym
Plant nitrogen demand not met by uptake from soil (kg N/ha)	Unknown	-
Soil water factor (0.0-1.0)	Unknown	-
Soil nitrate factor (0.0-1.0)	Unknown	-
Amount of water in soil profile	✓	BioSym & EnSym
Water content of soil profile at field capacity	✓	BioSym

5:2.3.2 Phosphorus Uptake

SWAT2005 calculates phosphorus in plants as a fraction of phosphorus in plant biomass, as a function of growth stage for the plant given optimal growing conditions.

Limitations:

The equations require a large amount of specific input data, which is limited in availability and is constrained to specific crop species that have been extensively researched.

SWAT2005 models phosphorus uptake in plants as a function of content under optimal conditions, there does not appear to be a means to simulate, model or calculate the impacts on plant phosphorus uptake under conditions that are outside the standard critical concentrations resulting in nutrient deficiency or toxicity (see section 2.3 Nutrient (N & P) requirements of plants).

It is unclear how well the equations can account for different plant types and mixed crops or landscapes.

Advantages:

Equations are able to differentiate potential phosphorus uptake for soil layers of different depths, and users are enabled to adjust the phosphorus distribution uptake parameter. This accounts for the differences in root density distribution with soil depth and the proportion of phosphorus uptake that occurs as a result of these differences through the soil profile. The model allows lower soil layers in the root zone to fully compensate for lack of nitrate in the upper layers. The phosphorus uptake distribution parameter also enables the user to account for nitrate loss in surface runoff from the top 10 mm of soil.

The model can account for different growth stages of a plant.

Review: The equations held within this section addressing phosphorus content and uptake of phosphorus by plants are simplistic with majority of the data required readily available. Based on this review, we consider the equations to be broadly applicable to Australian landscapes. However, the major downfall of the equations is the assumption of optimal conditions for plant growth. Unless this is accounted for in another section of the SWAT2005 model, then it poses a serious problem for asking good questions from the modelling and simulating capabilities of SWAT.

Input Data Required	Availability	Source
Normal fraction of phosphorus in plant biomass at maturity	✓	BioSym
Normal fraction of phosphorus in plant biomass at emergence	✓	BioSym
Heat units	✓	BioSym, EnSym & SILO
Optimal fraction of phosphorus in the plant biomass for the current growth stage	Limited	BioSym
Total plant biomass on a given day (kg ha^{-1})	Limited	BioSym
Potential increase in total plant biomass on a given day (kg/ha)	Unknown	-
Depth of root development in the soil (mm)	✓	BioSym
Potential phosphorus uptake for soil layer (kg N/ha)	Unknown	-
Phosphorus demand not met by overlying soil layers (kg N/ha)	Unknown	-
Phosphorus uptake distribution parameter	✓	BioSym
Growth stage factor (0.0-1.0)	✓	BioSym

<u>5:2.4 Crop Yield</u>

The amount of nitrogen and phosphorus removed in harvest events is modelled by SWAT and includes nutrient and plant material removed as part of the yield, which are assumed lost from the system and will not be added to residue or organic nutrient pools in the soil.

Limitations: No major limitations identified in this review.

Advantages:

Capability of accounting for crops where the Harvest Index (the fraction of above-ground plant dry biomass removed as dry economic yield) includes species that are harvested for both above- and below-plant matter (e.g. potatoes).

Can model based on optimal harvest index.

SWAT can calculate the amount of nitrogen or phosphorus that will be removed in each harvest event based on plant input data.

Can override the harvest index for use with a harvest only operation, enabling the model to assume that a portion of the plant biomass is being removed in addition to seed or other produce, using total biomass nitrogen and phosphorus rather than yield fractions.

Review: Data is readily available for the equations held within this chapter. Based on this review, we consider the equations applicable to Australian catchments. The constants used in the equations must be checked to ensure that they are suitable for use in Australia.

Data Input Requirements	**Availability**	**Source**
Potential harvest index for the plant at maturity given ideal growing conditions	✓	BioSym
Fraction of potential heat units accumulated for the plant on a given day in the growing season	✓	BioSym
Aboveground biomass on the day of harvest (kg ha^{-1})	Unknown	-
Total plant biomass on the day of harvest (kg ha^{-1})	Unknown	-
Fraction of total biomass in the roots the day of harvest	Limited	BioSym
Fraction of nitrogen in the yield (kg/ha)	✓	BioSym
Fraction of phosphorus in the yield (kg/ha)	✓	BioSym
Crop yield (kg/ha)	Unknown	-

SECTION 5 CHAPTER 3 ACTUAL GROWTH

This chapter enables growth constraints on plants to be incorporated and accounted for in the SWAT model. Constraints that can be accounted for by the SWAT model are extreme temperatures, and insufficient water, phosphorus and nitrogen. SWAT models the stress for these four parameters on a daily basis.

5:3.1 Growth Constraints

Water stress is simulated using actual and potential plant transpiration; temperature stress is simulated as a function of daily average air temperature and optimal temperature for plant growth; nitrogen stress is quantified/ modelled only for non-legumes by comparing actual and optimal nitrogen levels and nitrogen plant tissue contents; phosphorus stress is quantified/ modelled by comparing actual and optimal phosphorus levels and phosphorus plant tissue contents.

Limitations:

Temperature stress equations are based on the assumptions of a base temperature of 0°C and an optimal temperature of 15°C, it must be verified that these values are correct for Australian species and can be applied broadly across crops used in Australian agriculture.

Advantages:

Temperature stress equation uses the optimal plant growth temperature to determine if the simulated of calculated temperature exceeds or fall below the optimal temperature for plant growth.

SWAT provides a figure showing the impacts of mean air temperature on plant growth for a plant, based on the assumptions of a base temperature of 0°C and an optimal temperature of 15°C.

Nitrogen stress is only calculated for non-legumes, SWAT never allows legumes to experience nitrogen stress.

Review: The equations for growth constraints adequately address the main constraints to plants for the purpose of catchment management, and can be broadly applied to Australian catchments for crop, pasture and native forest environments providing sufficient and accurate Australian data is available to run the equations. The equations do not appear to be derived from validated sources or peer reviewed; however they appear to contain the key biological terms.

Input Data Required	Availability	Source
Base temperature for plant growth	✓	BioSym
Optimal temperature for plant growth	✓	BioSym
Actual transpiration on a given day (mm H_2O)	✓	BioSym &EnSym
Maximum plant transpiration on a given day (mm H_2O)	✓	BioSym
Total plant water uptake for the day (mm H_2O)		
Mean air temperature for day (°C)	✓	EnSym
Optimal mass of nitrogen stored in plant material for the current growth stage (kg N/ha)	Limited	BioSym
Actual mass of nitrogen stored in plant material for the current growth stage (kg N/ha)	Limited	BioSym
Optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha)	Limited	BioSym
Actual mass of phosphorus stored in plant material for the current growth stage (kg P/ha)	Limited	BioSym

5:3.2 Actual Growth

Plant growth factor is calculated as a function of the impact of stressors (temperature, water, nitrogen, phosphorus) on a given day

Limitations:

Plant growth factor equation does not consider soil characteristics as a limiting factor for plant growth.

Advantages:

Potential biomass prediction can be adjusted if one of the four stressors (temperature, water, nitrogen, phosphorus) is calculated as an important factor to include in the simulation.

Leaf area added on a given day can also be adjusted for daily plant stress.

Biomass override equation allows user to specify a totally biomass that the plant will produce each year, enabling SWAT to ignore the impact of variation in growing conditions from year to year, setting it to 1.00 for the HRU.

Review: Based on this review, we consider the equations for actual growth to adequately address the main constraints to plant growth for the purpose of catchment management, and can be broadly applied to Australian catchments for crop, pasture and native forest environments providing sufficient and accurate Australian data is available to run the equations. The equations do not appear to be derived from validated sources or peer reviewed; however they appear to contain the key biological terms.

Data Inputs Required	Availability	Source
Potential increase in plant biomass on a given day (kg/ha)	Unknown	-

5:3.3 Actual Yield

The actual yield of a crop is assessed using a harvest index, using equations from the previous chapter regarding Optimal Growth (equation 5:2.4.1).

Limitations:

No major limitations were identified in this review

Advantages:

SWAT includes a harvest index that accounts for plants under drought conditions, in association with a calculated water deficiency factor.

Harvest index override allows users to targets for the harvest index in plant and harvest only operations.

Harvest efficiency can be specified in the harvest only operation.

Review: The equations for actual yield can be applied to Australian catchments for crop, pasture and forest plantations providing sufficient and accurate Australian data is available to run the equations. The harvest index values must be validated for Australian The equations do not appear to be derived from validated sources or peer reviewed; however they appear to contain the key biological terms.

Data Inputs Required	Availability	Source
Harvest index for plants growing in drought conditions, the minimum harvest index allowed for the plant	Not Available	-
Harvest index target	Limited	-
Actual evapotranspiration on a given day	✓	EnSym
Potential evapotranspiration on a given day	✓	EnSym
The day in the plant growing season	✓	BioSym
The day of harvest if the plant is harvested before it reaches maturity or the last day of the growing season if the plant is harvested post maturity	Limited	BioSym
Material in the residue pool for the top 10 mm of soil	✓	BioSym

2.6 Tabulated review of catchment models

The following section provides a detailed tabulated review that is in accordance with the refined scope of this report (pers comms. Mark Eigenraam, Wayne Lewis). The following table provides a review of the top ten models. The top ten models were selected according to the commonality of use in the scientific community and how well each model, in contrast to the other models, met the requirements outlined in section 2.3.5. Models are arranged in alphabetical order, rather than order of suitability for the modelling tasks. An extended tabulated review (yet not exhaustive) of other available catchment models can be found in the appendix of this report. This table is also presented in alphabetical order.

Model acronym	Model name	Model purpose
SWAT	**S**oil & **W**ater **A**ssessment **T**ool	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.
AnnAGNPS	**Ann**ualized **A**gricultural **N**onpoint **P**ollution **S**ource Model	AnnAGNPS is a continuous simulation catchment-scale program developed based on the single-event model AGNPS. AnnAGNPS simulates quantities of surface water, sediment, nutrients, and pesticides leaving the land areas and their subsequent travel through the catchment

CAT (suit of models)	**C**atchment **A**nalysis **T**ool (3D spatially explicit model & CAT-1D-BC2C)	A model framework to model and simulate catchment processes. The CAT is a hydrological model that helps determine the movement of water and nutrients in a catchment via surface and subsurface pathways. CAT can also evaluate the impact of different farming systems and land use on vegetative growth, stream quality, productivity, stream flows and groundwater. CAT can account for crop yield, soil erosion, salinity and water dynamics, and has a suit of models that can look at biophysical responses such as crop growth, forest growth, water balance and groundwater.
Model acronym	Model name	Model purpose

CatchMODS	**Catch**ment scale **M**anagement **O**f **D**iffuse **S**ources model	Modelling framework that integrates SedNet, enabling calculation of average annual nitrogen, phosphorus and sediment loads. Designed to simulate conditions and the effects of management activities on the quality of receiving waters.
CENTURY -> DAYCENT	CENTURY Soil Organic Matter Model Environment modified for a daily time step	A land surface sub-model of CENTURY. Simulates plant-soil, carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests and savannas, capable of simulating detailed daily soil water and temperature dynamics and trace gas fluxes (CH4, N2O, NOX and N2)
EMSS	**E**nvironmental **M**anagement **S**upport **S**ystem	Predicts runoff and total suspended sediment on a daily time-step.
LASCAM	**La**rge **S**cale **Ca**tchment **M**odel	Hydrological salt, sediment and nutrient transport model
MODFLOW	**MODFLOW**	MODFLOW is used to simulate systems for water supply, containment remediation and mine dewatering. Primarily a groundwater flow model
SWIM	**S**oil and **W**ater **I**ntegrated **M**odel	SWIM is a model that integrates water quality, weather, hydrology, erosion, crop growth, and nutrients (nitrogen and phosphorus) at the catchment scale.
Model acronym	Model name	Model purpose
WaterCAST	**Water** and **C**ontaminant	This tool has been developed

	Analysis **S**imulation **T**ool; ***Replacement for E2***	to facilitate the improved and consistent evaluation of flows, loads and concentrations of constituents, under scenarios that include actual or planned changes in land use, land management, climate variability and climate change. Supports constituent generation for sediment, nitrogen, phosphorus and litter. Also Flexible for both quantity and quality of water fro non urban catchment to receiving waters - see aquatic R&D for further info.

Model acronym	Daily Time Step	Sub Models	Developer/Owner
SWAT	Yes	AVSWAT (ArcView SWAT), SWIM, SWAT-G, ESWAT, GLEAMS, CREAMS, EPIC, SWRRB, erosion and sediment yield are measured using the MUSLE- modified universal soil loss equation	United States Department of Agriculture, Agricultural Research Service (USDA-ARS)
AnnAGNPS	Yes, Long term; daily or sub-daily steps.	An adaption of AGNPS, uses RUSLE and HUSLE	USDA Agricultural Research Service (ARS) and the USDA Natural Resources Conservation Service (NRCS)
CAT (suit of models)	Yes, can be used to model on a daily, monthly yearly or mean annual basis.	MODFLOW, BC2C, 2CSalt, Zhang FEFLOW, CAT GW, CAT-1D, CAT build, SWAT, CERES-Wheat, PERFECT, GRASP, GRAZPLAN, SGS, EPIC, PG forest growth model, PERFECT, SHE	DPI Victoria & CRC for Salinity
CatchMODS	The hydrological model operates at a daily time-step, whilst predictions for pollutant loads are annual (nutrients and sediments)	SedNet, IHACRES	iCAM - Integrated Catchment Assessment and Management Centre

Model acronym	Daily Time Step	Sub Models	Developer/Owner
CENTURY -> DAYCENT	Yes	The sub-model of Century (V4) Daycent (5) adds layered soil temperature, a trace gas submodel, a more detailed soil hydrology submodel, and explicitly represents inorganic N as either NO3– or NH4+	Natural Resources Ecology Laboratory, Colorado State University; USDA-ARS
EMSS	Yes	Two components: hydrological model and a pollutant export load model. SIMHYD, colobus, Marmoset, Mandrill	Cooperative Research Centre for Catchment Hydrology (CRCCH).
LASCAM	Yes		Centre for Water Research (CWR), University of Western Australia
MODFLOW	Yes	Numerous sub-models and re-inventions of MODFLOW are available. Too numerous to list	U.S. Geological Survey (USGS)
SWIM	Yes	SWAT, MATSALU, EPIC, GRASS interface, MUSLE, SCS CN method	Potsdam Institute for Climate Impact Research
WaterCAST	Yes	AWBM, SimHYD, Sacramento and SMAR	eWater CRC

Model acronym	Primary reference	Peer reviewed	Scale/resolution	Licence/Access
SWAT	Arnold et al 1998; Weeks et al 2008; Neitsch et al.2001; Neitsch et al. 2005	Yes	Catchment scale, intended to be applied in catchments up to 25,000 km^2	Free Access
AnnAGNPS	Not found	Yes	0.4 to 16 ha to represent upland and channel conditions, catchment scale limited by data availability and computer, catchments of about 200 km^2 memory, drainage areas up to 300,000 ha	Non-proprietary (required to register prior to download). No fee. http://msa.ars.usda.gov/ms/oxford/nsl/AGNPS.html
CAT (suit of models)		Yes	Paddock to catchment scale	Not yet identified
CatchMODS	Newham et al. 2002	Yes	Catchment scale	Licence is required for SedNet, but no fee charged, Not clear on CatchMods access.
CENTURY -> DAYCENT	Parton et al. 1998	Yes	Catchment scale, down to 1kmX1km. Soil layers 4+, 1cm resolution	Freely downloadable, however not yet able to locate website
EMSS	Vertessy et al. 2001	Yes	Catchment and sub-catchment scale	Not yet identified

LASCAM	Sivapalan et al. 1996	Yes	Sub-catchments, ranging in size from 1-10km^2	Not yet identified
Model acronym	Primary reference	Peer reviewed	Scale/resolution	Licence/Access
MODFLOW	http://water.usgs.gov/nrp/gwsoftware/modflow.html	Yes	Not specified, determined on the basis of spatial variability and data availability	This product is no longer commercially available. However, it can be downloaded for free at the download site http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html
SWIM	Krysanova et al., 1998	Yes	Catchments with an area of 100 to 10000 km^2	Free access to software http://www.scisoftware.com/products/swim_details/swim_details.html
WaterCAST	Argent et al. 2004	Yes	The tool has been designed to operate best on rural and peri-urban catchments between 1 km^2 and 5000 km^2	A licence agreement is part of the installation procedure. You must acknowledge that you have read, understood and agree to be bound by the software licence agreement to be able to proceed with the installation.

Model acronym	Nitrogen	Phosphorus	Sediments	Surface water	Groundwater	Pesticides	Climate
SWAT	✓	✓	✓	✓	✓	✓	✓
AnnAGNPS	✓	✓	✓	✓	Under development	✓	✓
CAT (suit of models)	✓	✓	✓	✓	✓	✓	✓
CatchMODS	✓ (TN)	✓ (TP)	✓	✓	×	×	✓
CENTURY -> DAYCENT	✓	✓	Not determined	✓	×	×	✓
EMSS	✓ (TN)	✓ (TP)	✓	✓	✓	Not determined	✓
LASCAM	✓	✓	✓	✓	✓	×	×
MODFLOW	×	×	✓	✓	✓	×	×
SWIM	✓	✓	✓	✓	✓	× but models diffuse pollution	✓
WaterCAST	✓	✓	The EMSS Sediment Export Coverage plug-in is largely untested - see Drewry et al 2006 who discusses complications of this aspect.	✓	Under development	×	✓

Model acronym	Limitations	Benefits
SWAT	Requires large data inputs	Incorporates a diverse range of equations that enables SWAT to model several aspects of a catchment: climate, hydrology, nutrients/pesticides, erosion, land cover/plant growth, management practises, main channel processes and water bodies.
AnnAGNPS	Output is only monthly or annual, all runoff and associated sediment, nutrient, and pesticide loads for a single day are routed to the catchment outlet before the next day simulation begins (regardless of how many days this may actually take); • There are no mass balance calculations tracking inflow and outflow of water; • There is no tracking of nutrients and pesticides attached to sediment deposited in stream reaches from one day to the next; • Point sources are limited to constant loading rates (water and nutrients) for entire simulation period; • Pre-processing software (flow net generator and input editor) are written in Visual Basic for a Windows environment so they will not operate on a DOS-only system; • There is no allowance for spatially variable rainfall.	AnnAGNPS is a distributed parameter, catchment scale model that is used for continuous simulations. AnnAGNPS can be used to study the effect of BMPs (agricultural practices, ponds, grassed waterways, irrigation, tile drainage, vegetative filter strips and riparian buffers).

Model acronym	Limitations	Benefits
CAT (suit of models)	Sufficient validation of the CAT suit of models remains challenging, and the models require large data inputs.	Explicitly links landscape models. Framework includes models for crops, pastures, salt affected landscape and forests. Acounts for inter-annual climatic events. Daily excess water is partitioned into groundwater recharge and lateral flow, accounting for landscape position as a function of soil type and slope. Model parameterisation is kept to a minimum.
CatchMODS	TP is only transported adsorbed to sediment	No specific benefits identified during the review
CENTURY -> DAYCENT	Detailed process representation does require a lot of information, and parameters to be defined.	Freely downloadable and has been widely used in Victoria, South Australia and Queensland for different soul and vegetation types. Also simulates carbon & Sulfur
EMSS	Models daily loads at a sub-catchment scale, however it is recommended that the daily output is aggregated to monthly loads (Drewry et al 2006). Limited by availability of local data. All runoff and associated sediment, nutrient, and pesticide loads for a single day are routed to the catchment outlet before the next day simulation. There is no tracking of nutrients and pesticides attached to sediment deposited in stream reaches from one day to the next. Point sources are limited to constant loading rates (water and nutrients) for the entire simulation period. Spatially variable rainfall is not allowed.	Uses readily available input data
LASCAM	Requires 18 parameters fo N alone, 11 for P and 6 for sediment, which may make this an inappropriate model.	No specific benefits identified during the review

Model acronym	Limitations	Benefits
MODFLOW	A large amount of information and a complete description of the flow system is required to make the most efficient use of MODFLOW. In situations where only rough estimates of the flow system are needed, the input requirements of MODFLOW may not justify its use. The water must have a constant density, dynamic viscosity (and consequently temperature) throughout the modelling domain	No specific benefits identified during the review
SWIM	A model adaptation of SWAT and MATSALU that was adjusted for use in European climates	Continuous-time spatially distributed catchment model. Incorporates user-friendly features such as dialog boxes and graphic interfaces for numerous data input and various data output function. SWIM can be used to model and manage generated waste. Can simulate diffuse pollution, climate, crop yields and land use
WaterCAST	• Soil water processes are not considered explicitly The predictive power of WaterCAST is a function of the available component models, so if the available models are not appropriate to the problem or available data, predictive performance will be reduced. • Development of new component models is a complex process requiring specialist knowledge, so the capacity for some users or their agents to develop new component models may be limited. Steady state representations of sediment generated from a parcel of land.	The ability to incorporate spatially and temporally variable cover estimates for predict sediment generation into WaterCast is a useful advance in catchment water quality modelling. Can model impacts of extreme disturbance events such as drought, bushfire, flood and construction.

Section Three – Knowledge gaps and future needs

3.1 Synthesis

This report presents a review of the current and available literature relating to terrestrial nutrient cycling, nutrient transport and vegetation dynamics. The available literature provides good background information to assist catchment managers with regards to a basic understanding of terrestrial nutrient cycling (specifically nitrogen and phosphorus), nutrient transport and vegetation dynamics. Our synthesis of the literature aimed to provide additional insights to inform and assist environmental management decisions and highlight the knowledge gaps for directing future research priorities within the EnSym framework. Thus, while this report does not aim to be exhaustive, it does identify areas where further study is required.

The examination of several case studies and examples of plant nutrient requirements and plant tissue concentrations highlighted the absence of complete and accurate data for the crop species barley and a generalised tree and stand of trees. The concept and understanding of a 'generalised tree' needs further development to better address the question of nutrient requirements and concentrations of plant tissues in Australia. Such information is also relevant to the identified need to determine optimal growth conditions for plants in Australia.

The SWAT model, considering the equations that underwent review according to the scope of this project, was found to be satisfactory for use within the EnSym framework. Limitations were identified in the SWAT model: SWAT does not adequately model groundwater, drought, and salinity and has no means to account for the impacts of fire on terrestrial nutrient cycling. However, after undertaking a comparative study (non-exhaustive given time constraints of the project) of identified catchments models, SWAT was found to be the most appropriate model to use within the EnSym framework to meet the modelling requirements outlined in discussion with the DSE during the scope development of this project (pers comm. Mark Eigenraam, Wayne Lewis). Further research is required to incorporate models into the EnSym framework to fill the gaps identified by this study in the SWAT model.

3.2 Identify key knowledge gaps around the SWAT model

Based on this review, and our evaluation of the selected equations sets held within SWAT, it appears that SWAT is suited to the required modelling tasks (pers comms Mark Eigenraam, Wayne Lewis). SWAT satisfactorily meets the model requirements outlined in section 2.5.

The key knowledge gaps identified in the SWAT model were the apparent lack of equations to address drought, salinity, groundwater and fire, all of which are important aspects to include when considering an Australian and specifically Victorian environment. Model comparison revealed the SWAT model to be the most successful model in addressing the modelling tasks required. The process of model comparison informed us that there are a suit of models available that could/can be used within the EnSym framework to fill the gaps in the SWAT model e.g.

BC2C or Salt2C could be used to address salinity. Although recommendations could be made as to the incorporation of other models into the EnSym framework, this could only be done on surface level, and hence we will refrain from providing such recommendations and suggest that a more detailed study is required to adequately recommend (with confidence) appropriate models to incorporate into EnSym.

Key knowledge gaps identified from the undertaken literature review:

- There appears to be a knowledge gap in the current scientific literature regarding best management practice for the use of riparian zones in managing nutrient deposition into waterways from upland sources of nutrients into aquatic systems, particularly in Victoria (e.g. fertilizers, animal wastes, and surface runoff). This highlights the need for further studies to be undertaken to better determine the role that riparian vegetation plays in nutrient interception and cycling and advance our understanding of the movement of nutrients between the aquatic and terrestrial environments within the context of nutrient cycling.
- Thus far, no studies that directly address the impacts of total tree removal on catchment nutrient dynamics have been identified in Australian literature. Our current understanding of the long-term impacts and implications of clear-felling in Victorian catchments are far from complete. Future research should investigate the impacts of whole-tree removal within Australian catchments, to determine if the results from previous studies correlate with the dynamics in Australian catchments, and lead to the creation of effective management practices.
- The creation of a central database for input information for modelling purposes is required to bridge the data gap between those who collected it and those who will use it for research and management purposes. This will increase accessibility to a variety of useful resources and assist in accurate and complete environmental assessments and understanding of pollutant loads and movements within catchments.
- Grasses and shrubs play an important role in nutrient uptake in natural landscapes, especially in riparian regions. Future research should include a determination of typical grass and shrub plant tissue nutrient requirements and concentrations to better assist in restoration initiatives and catchment management practises.
- Research must be undertaken to close the gap on forest dynamics concerning nutrient content of a typical stand of trees in an Australian landscape. This must be accompanied by a definition of a typical stand of trees, incorporating stand age, average tree diameter at breast height (DBH) and tree height.
- Further research into the nutrient concentration of barley plant (nitrogen and phosphorus) tissue concentrations must be undertaken to determine the tissue concentrations to the

same standard of knowledge as provided for the wheat plant. The information may be available; however during this review it was not identified.

3.2 Addressing knowledge gaps: research priorities for the validation and improvement of the SWAT model

- Very little validation of the SWAT model has been undertaken in Australia. Only four publications thus far from Australia have been identified (Sun & Cornish, 2005, Sun & Cornish, 2006, Watson *et al.*, 2003, Watson *et al.*, 2005). Validation is of the SWAT model in Australia is essential before the model is used within the EnSym framework. This is required to determine the accuracy of the equations in the Australian environment.

- It is recognised that the DSE is currently developing groundwater models and equations, however the tending to over-predicted base flows and recession rates, and hence underestimates soil interflows must be noted as a major limitation of the SWAT model.

- Based on the review of the SWAT equations, the need for further efforts in acquiring adequate and accurate soil temperature data was highlighted.

- The applicability of the equations in SWAT addressing phosphorus was limited by the absences of sufficient phosphorus data. This highlights the need to invest in research to improve the soil phosphorus database.

- Groundwater and tree growth model components of SWAT must be modified to enable water balance modelling with greater accuracy in Australian catchments.

- In the cases where equations are not peer reviewed, constants used in the equations held within SWAT must be validated.

- Data availability is a major limitation on implementing the SWAT model equations in the EnSym framework. It appears that more research must be undertaken to develop access to the required data inputs. For extensive details on data requirements see section 2.5. However, we do highlight the need to identify optimal growth temperatures in the context of a changing climate and concomitant shifts in agriculture.

- Appropriate land use category for including natural vegetation cover types must be included into the SWAT model for application to Australian environments.

- Equations or models must be incorporated into the SWAT model or EnSym framework to account for the impact of fire to nutrient transport and cycling.

- Run-off curve number must be altered to account for soil conditions under tilling practises.

- Equations must be altered or extended to be able to select and account for forest plantations, native vegetation cover types (scrub, mallee, temperate rainforest, dry sclerophyll forest) and/or fire affected landscapes.

- Temperature stress equations are based on the assumptions of a base temperature of 0°C and an optimal temperature of 15°C, it must be verified that these values are correct for Australian species and can be applied broadly across crops used in Australian agriculture.

It is important to note that some future research outlined and suggestions made in the recommendations may already be underway.

APPENDIX

Appendices 1. Nitrogen equations evaluation summary

Appendices 2. Nitrogen equation data input requirements

Appendices 3. Phosphorus equations evaluation summary

Appendices 4. Phosphorus equations data input requirements

Appendices 5. Nutrient transport equation evaluation summary

Appendices 6. Nutrient transport equation data input requirements.

Appendices 7. Tabulated review of identified catchment models

Equation	Applicable	Valid	Source known	Availability
3:1.1.1	✓ needs validating for Australian values	✓	✗	Limited
3:1.1.2	✓ needs correcting for Australian values	✓	✗	✓
3:1.1.3	✓ needs validating for Australian values	✓	✗	✓
3:1.1.4	✓ needs validating for Australian values	✓	✗	✓
3:1.1.5	✓ needs validating for Australian values	✓	✗	✗
3:1.1.6	✓	✓	✗	Limited
3:1.2.1	✓	✓	✓ Seligman and van Keulen (1981)	Limited
3:1.2.2	✓	✓	✓ Seligman and van Keulen (1981)	✓
3:1.2.3	✓ needs validating for Australian values	✓	✓ Seligman and van Keulen (1981)	✓
3:1.2.4	✓	✓	✗	Limited
3:1.2.5	✓ needs validating for Australian values	✓	✗	Limited
3:1.2.6	✓ needs validating for Australian values	✓	✗	✓
3:1.2.7	✓	✓	✗	Limited
3:1.2.8	✓ needs validating for Australian values	✓	✗	✗
3:1.2.9	✓ needs validating for Australian values	✓	✗	✓
3:1.3.1	✓ needs correcting for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	Limited
3:1.3.2	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	Limited
3:1.3.3	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✓
3:1.3.4	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	N/A
3:1.3.5	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✗
3:1.3.6	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✗
3:1.3.7	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✗
3:1.3.8	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979)	✗
3:1.3.9	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979)	✗
3:1.3.10	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979)	✗
3:1.3.11	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✗
3:1.3.12	✓ needs validating for Australian values	✓	✓ Reddy et al. (1979); Godwin et al. (1984)	✓
3:1.4.1	✓ needs validating for Australian values	✓	✗	✓

Equation	Applicable	Valid	Source known	Availability
3:1.4.2	✓ needs validating for Australian values	✓	✗	✓
3:1.5.1	✓ needs validating for Australian values	✓	✗	Limited
3:1.7.1	✓ needs validating for Australian values	✓	✗	Limited
3:1.9.1	✓	✓	Venetis (1969); Sangrey et al. (1984)	Limited
3:1.9.2	✓	✓	✗	Limited
3:1.9.3	✓	✓	✗	Limited
3:1.9.4	✓	✓	✗	Limited
3:1.9.5	✓	✓	✗	Limited
3:1.9.6	□needs validating for Australian values	□	□	Limited

Appendices 1. Nitrogen equation evaluation summary

Data Inputs Required	Source	Equations
Nitrate concentration in soil layer (mg/ks or ppm)	BioSym	3:1.1.1; 3:1.2.5; 3:1.7.1
Depth of the soil layer (mm)	? BioSym	3:1.1.6
Depth from the soil surface (mm)	? EnSYm	3:1.1.1; 3:1.3.4
Bulk density of soil layers (Mg/m^3)	BioSym	3:1.1.6
Material in the residue pool for the top 10mm of soil kg ha^{-1}	Not Available	3:1.1.5
Material in the residue in the soil layer kg/ha	Not Available	3:1.2.5; 3:1.2.6
Amount of organic carbon (%) in the soil layer	BioSym & EnSym	3:1.1.2; 3:1.4.1
Initial humic organic nitrogen in soil layer (mg/kg or ppm)	BioSym	3:1.1.3; 3:1.1.4
Concentration of nitrogen in the soil layer (mg/kg or ppm)	BioSym & EnSym	3:1.1.6
Rate coefficient for mineralization of the humus active organic nutrients	BioSym	3:1.2.4
Rate coefficient for mineralization of the residue fresh organic nutrients	Not Available	3:1.2.7
Soil temperature for each soil layer (°C)	BioSym (limited)	3:1.2.1; 3:1.3.1
Soil water content for each soil layer on a given day (mm H_2O)	EnSym	3:1.2.2; 3:1.3.2; 3:1.3.3; 3:1.7.1
Nitrogen in the active organic pool (kg N/ha)	BioSym (limited)	3:1.2.3; 3:1.2.4
Fraction of humic nitrogen in the active pool (kg N/ha)	BioSym	3:1.1.3; 3:1.1.4; 3:1.2.3; 3:1.2.4

Data Inputs Required	Source	Equations
Nitrogen in the fresh organic pool in the soil layer (kg N/ha)	BioSym	3:1.2.5; 3:1.2.9
Nitrogen in the stable organic pool (kg N/ha)	? BioSym	3:1.2.3
Phosphorus in the fresh organic pool (kg P/ha)	? BioSym	3:1.2.6
Phosphorus in solution (kg P/ha)	BioSym/set by SWAT if not specified	3:1.2.6
Soil water content for each soil layer at field capacity (mm H_2O)	BioSym	3:1.2.2; 3:1.3.2; 3:1.3.3
Soil water content for each soil layer at wilting point (mm H_2O)	BioSym	3:1.3.2; 3:1.3.3
Concentration of nitrogen in rainfall (mg N/L)	BioSym	3:1.5.1
Daily precipitation data	SILO & EnSym	3:1.5.1
Rate coefficient for denitrification	? Not Available	3:1.4.1
Initial mount of nitrate in the shallow aquifer on a given day (kg N/ha)	BioSym	3:1.9.6
Amount of nitrate in the shallow aquifer at the end of the day (kg N/ha)	? Not Available	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Delay time for aquifer recharge (days)	? EnSym and SILO	3:1.9.1
Half-life of nitrate in the shallow aquifer (days)	?	3:1.9.6
Ground water/base flow into main channel (daily)	Not Available	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Recharge entering deep aquifer	Not Available	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Amount of water moving through soil zone	? BioSym & EnSym	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Daily evaporation data (mm H2O)	BioSym & EnSym	3:1.7.1
Amount of water stored in the shallow aquifer at the end of a day (mm H_2O)	? Not Available	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Amount of recharge entering the aquifer on a given day (mm H_2O)	? Not Available	3:1.9.2; 3:1.9.3: 3:1.9.4; 3:1.9.5
Rate constant for removal of nitrate in the shallow aquifer (1/day)	? Not Available	3:1.9.6

Appendices 2. Nitrogen equation data input requirements

Equation	Applicable	Valid	Source known	Data available
3:2.1.1.1	✓	✓	✓ Jones et al. (1984)	×
3:2.1.1.2	✓	✓	✓ Jones et al. (1984)	×
3:2.1.1.3	✓ need to validate N:P ratio for Australian soil	✓	×	✓
3:2.1.1.4	✓ need to validate N:P ratio for Australian soil	✓	×	×
3:2.1.1.5	✓	✓	×	N/A
3:2.2.1	✓ need to validate constants for Australian soils	✓	✓ Jones et al. (1984)	Limited
3:2.2.2	✓	✓	✓ Jones et al. (1984)	✓
3:2.2.3	✓	✓	✓ Jones et al. (1984)	✓
3:2.2.4	✓	✓	✓ Jones et al. (1984)	✓
3:2.2.5	✓	✓	× not required	✓
3:2.2.6	✓	✓	×	Limited
3:2.2.7	✓	✓	×	Limited
3:2.2.8	✓ need to validate constants for Australian soils	✓	×	Limited
3:2.2.9	✓ need to validate constants for Australian soils	✓	×	✓
3:2.2.10	✓ need to validate constants for Australian soils	✓	×	Limited
3:2.2.11	✓ need to validate constants for Australian soils	✓	×	Limited
3:2.3.1	✓	✓	✓ Jones et al. (1984)	×
3:2.3.2	✓	✓	✓ Jones et al. (1984)	×
3:2.3.3	✓ need to validate constants for Australian soils	✓	✓ Jones et al. (1984)	×
3:2.3.4	✓ need to validate constants for Australian soils	✓	✓ Jones et al. (1984)	×
3:2.3.5	✓ need to validate constants for Australian soils	✓	✓ Jones et al. (1984)	×
3:2.4.1	✓ need to validate constants for Australian soils	✓	×	×

Appendices 3. Phosphorus equations summary

Data Inputs Required	Data Source	Equation
Initial soluble P concentration in soil layer (mg/kg or ppm)	BioSym	3:2.1.1; 3:2.2.7; 3:2.3.2; 3:2.3.3; 3:2.4.1
Initial humic organic nitrogen in soil layer (mg/kg or ppm)	BioSym	3:2.1.3
Phosphorus availability index	Not Available	3:2.1.1; 3:2.3.2; 3:2.3.3
Material in the residue pool for the top 10 mm of soil (kg ha^{-1})	Not Available	3:2.1.4
Bulk density data for soil layer (Mg/m^3)	BioSym	3:2.1.5; 3:2.4.1
Rate coefficient for mineralization of the humus active organic nutrients	BioSym	3:2.2.5
Rate coefficient for mineralization of the residue fresh organic nutrients	Not Available	3:2.2.8
Phosphorus percolation coefficient (10 m^3/Mg)	BioSym	3:2.4.1
Soluble phosphorus concentration in groundwater flow (mg P/L)	Not Available	
Water content of the soil layer at field capacity	BioSym	3:2.2.2
Soil temperature data	BioSym (limited)	3:2.2.1
Nitrogen in the stable organic pool (kg N/ha)	BioSym (limited)	3:2.2.3; 3:2.2.4
Nitrogen in the active organic pool (kg N/ha)	BioSym (limited)	3:2.2.3; 3:2.2.5
Nitrate in the soil layer (kg N/ha)	BioSym (limited)	3:2.2.6
Residue in the layer (kg/ha)	Not Available	3:2.2.6; 3:2.2.7
Nitrogen in the fresh organic pool per soil layer (kg N/ha)	BioSym (limited)	3:2.2.6
Residue decay rate constant	?	3:2.2.10; 3:2.2.11
Amount of P in solution after fertilization and incubation	BioSym (limited)	3:2.3.1
Amount of P in solution before fertilization	BioSym (limited)	3:2.3.1
Amount of soluble P fertilizer added to sample	BioSym (limited)	3:2.3.1
Phosphorus in the active organic pool (kg N/ha)	BioSym (limited)	3:2.3.2; 3:2.3.3; 3:2.3.4; 3:2.3.5
Phosphorus in the stable organic pool (kg N/ha)	BioSym (limited)	3:2.3.4; 3:2.3.5
Amount of water percolating to the first soil layer on a given day (mm H_2O)	BioSym (limited)	3:2.4.1

Appendices 4. Phosphorus equation data input requirements

Equation	Applicable	Valid	Source known	Data available
4:2.1.2	✓ need to validate constants for Australian soils	✓	×	Limited
4:2.1.3	✓	✓	×	✓
4:2.1.4	✓	✓	×	✓
4:2.1.5	✓	✓	×	✓
4:2.1.6	✓	✓	×	Limited
4:2.1.7	✓	✓	×	Limited
4:2.1.8	✓	✓	×	Limited
4:2.2.1	✓ need to validate constants for Australian soils	✓	✓ McElroy et al (1976); Williams and Hann (1978)	✓
4:2.2.2	✓	✓	✓ McElroy et al (1976); Williams and Hann (1978)	✓
4:2.2.3	✓ need to validate constants for Australian soils	✓	✓ Menzel (1980)	Limited
4:2.2.4	✓ need to validate constants for Australian soils	✓	✓ Menzel (1980)	Limited
4:2.3.1	✓	✓	×	×
4:2.4.1	✓	✓	✓ McElroy et al (1976); Williams and Hann (1978)	×
4:2.4.2	✓	✓	✓ McElroy et al (1976); Williams and Hann (1978)	Limited
4:2.4.3	✓ need to validate constants for Australian soils	✓	✓ Menzel (1980)	Limited
4:2.4.4	✓ need to validate constants for Australian soils	✓	✓ Menzel (1980)	Limited
4:2.5.1	✓ need to validate constants for Australian soils	✓	×	Limited
4:2.5.2	✓ need to validate constants for Australian soils	✓	×	Limited
4:2.5.3	✓ need to validate constants for Australian soils	✓	×	Limited
4:2.5.4	✓ need to validate constants for Australian soils	✓	×	Limited
4:2.5.5	✓ need to validate constants for Australian soils	✓	×	Limited

Appendices 5. Nutrient transport equations summary

Data Inputs Required	Source	Equation
Nitrate percolation Coefficient	BioSym	4:2.1.5; 4:2.1.6
Fraction of porosity from which anions are excluded	BioSym	4:2.1.2
Concentration of nitrate in a soil layer	BioSym	4:2.1.2
Amount of mobile water in the soil layer	BioSym & EnSym	4:2.1.7
Saturated water content of the soil layer (mm H2O)	?	4:2.1.2
Nitrogen content of the fresh organic pool for top 10 mm	BioSym	4:2.2.1; 4:2.2.2
Soil bulk density data for the first soil layer (Mg/m^3)	BioSym	4:2.2.2; 4:2.3.1; 4:2.4.2
Organic nitrogen enrichment ratio	?	4:2.2.1
Sediment yield on a given day (metric tons)	?	4:2.2.1; 4:2.2.4; 4:2.4.1; 4:2.4.4
The area (ha) of each HRU	EnSym	4:2.2.1; 4:2.4.1; 4:2.4.4
Amount of surface runoff on a given day	EnSym	4:2.2.4; 4:2.3.1
Amount of phosphorus in solution for the top 10 mm (first soil layer)	BioSym	4:2.3.1
Phosphorus soil partitioning coefficient (Mg/m3)	BioSym	4:2.3.1
Concentration of phosphorus attached to sediment in the first soil layer (10 mm)	BioSym & EnSym	4:2.4.1
The amount of P in the stable mineral pool for the first soil layer (10 mm) (kg P/ha)	BioSym	4:2.4.2
The amount of P in the active mineral pool for the first soil layer (10 mm) (kg P/ha)	BioSym	4:2.4.2
The amount of P in the fresh organic P pool (kg P/ha)	BioSym	4:2.4.2
The concentration of sediment in surface runoff ($Mg\ sed/m^3$)	?	4:2.2.3; 4:2.4.3
Amount of P discharged to the main channel in surface runoff on a given day (kg P/ha)	BioSym & EnSym	4:2.5.4
Amount of nitrate discharged to the main channel in surface runoff on a given day (kg P/ha)	BioSym & EnSym	4:2.5.1
Phosphorus enrichment ratio	?	4:2.4.1
Amount of surface runoff nitrate generated per day in an HRU (kg N/ha)	?	4:2.5.1
Surface runoff nitrate stored or lagged from the previous day (kg N/ha)	?	4:2.5.1

Amount of lateral flow nitrate generated per day in an HRU (kg N/ha)	?	4:2.5.2
Lateral flow nitrate stored or lagged from the previous day (kg N/ha)	?	4:2.5.2
Data Inputs Required	**Source**	**Equation**
Amount of surface runoff organic nitrogen generated per day in an HRU (kg N/ha)	?	4:2.5.3
Surface runoff organic nitrogen stored or lagged from the previous day (kg N/ha)	?	4:2.5.3
Amount of lateral flow organic nitrogen generated per day in an HRU (kg N/ha)	?	4:2.5.3
Lateral flow organic nitrogen stored or lagged from the previous day (kg N/ha)	?	4:2.5.3
Sediment-attached P discharged to the main channel in surface run off (kg P/ha)	?	4:2.5.4
Surface runoff lag coefficient	?	4:2.5.1; 4:2.5.3; 4:2.5.5

Appendices 6. Nutrient transport equation data requirements

Appendices 7. Tabulated review of identified catchment models

Model acronym	Model name	Model purpose
2CSalt	**2CSalt**	2CSalt is used to investigate the impact of land-use change on the generation of water and salt. 2CSalt is also aimed at exploring seasonal impacts of land-use change. 2CSalt provides water balance equations, and includes both a hill-slope and an alluvial groundwater store. It produces monthly stream flow and salt load estimates.
ANNEX	**An**nual **N**utrient **Ex**port	Estimation of nutrient transport, source apportionment, separation of human impact from anthropogenic, and to evaluate climate and management scenarios.
ANSWERS	**A**real **N**on-point **S**ource **W**atershed **E**nvironment **R**esponse **S**imulation	To model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion. Daily water balance, infiltration, runoff and surface water routing, drainage, river routing, ET, sediment detachment, sediment transport, nitrogen and phosphorous transformations, nutrient losses through uptake, run-off, and sediment.
APSIM	**A**gricultural **P**roduction **S**ystem s**IM**ulator	To simulate biophysical processes in farming systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk.

Model acronym	Model name	Model purpose
BC2C	**B**iophysical **C**apacity to **C**hange	A conceptual mass based model to simulate the long-term average salt and water yield of whole catchments. A stand alone prioritization tool for estimating the changes in catchment salt generation and water balance as a result of land-use changes. Used to estimate the impact of changes in forest cover on stream volume and salt load.
CASC2D	**CASC**ade of planes in **2-D**imensions	The two-dimensional model CASC2D simulates surface runoff from rainfall, and precipitation in excess of infiltration. Predicts peak flows, overland flow, channel routing and models spatial precipitation domains.
CatchmentSIM	**Catchment Sim**ulation Solutions	CatchmentSIM is a 3D-GIS topographic parameterisation and hydrologic analysis model. The model automatically delineates watershed and sub-catchment boundaries, generalises geophysical parameters and provides in-depth analysis tools to examine and compare the hydrologic properties of sub-catchments. CatchmentSIM has been used to help setup models for a wide range of water resource management projects, flood and floodplain management studies, hydrologic investigations, water quality studies, environmental flow investigations and urban stormwater project

Model acronym	Model name	Model purpose
CMSS	**C**atchment **M**anagement **S**upport **S**ystem	Predicts impacts of nutrient management on water quality and nutrient load delivered to rivers, especially the effect of total P and total N reaching waterways within a catchment.
CREAMS	**C**hemicals, **R**unoff, and **E**rosion from **A**gricultural **M**anagement **S**ystems	Soil pesticide-modified from GLEAMS. However, this model is incorporated into the SWAT model, therefore no further review undertaken.
DNDC	**DeN**itrification **DeC**omposition	Simulates carbon and nitrogen biogeochemistry in agricultural systems.
DRAINMOD	**DRAINMOD**	Simulates the hydrology of poorly drained, high water table soils for long periods of climatological record (e.g. 50 years). The model predicts the effects of drainage and associated water management practices on water table depths, the soil water regime and crop yields.
DWSM	**D**ynamic **W**atershed **S**imulation **M**odel	DWSM simulates distributed surface and sub-surface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural and rural watersheds during single rainfall events.
EPIC	**E**rosion **P**roductivity **I**mpact **C**alculator	This model is incorporated into the SWAT model, therefore no further review undertaken.

Model acronym	Model name	Model purpose
ESWAT	**E**xtended **S**oil and **W**ater **A**ssessment **T**ool	An extension and modified version of SWAT that uses a time step of a user-defined fraction of an hour and an hourly time step to calculate the rainfall/runoff and the in-stream river routing processes, respectively.
Feflow	**F**inite **E**lement Subsurface **Flow** and Transport system	A professional software package for modelling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface. Simulating groundwater flow, mass transfer and heat transfer in porous media.
GLEAMS	**G**roundwater **L**oading **E**ffects of **A**gricultural **M**anagement **S**ystems	Pesticide modelling tool. This model is incorporated into the SWAT model, therefore no further review undertaken.
HBV-NP	**HBV-NP**	A modification of the HBV-N model that simulates both nitrogen (N) and phosphorus (P) transport and transformation at the catchment scale
HSPF	**H**ydrologic **S**imulation **P**rogram **F**ortran	Simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. Runoff and water quality constituents on pervious and impervious land areas, movement of water and constituents in stream channels and mixed reservoirs, and part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.

Model acronym	Model name	Model purpose
HYDRUS	**HYDRUS**	HYDRUS is used for analysing water flow and solute transport processes in soils and groundwater (water, heat, and solute movement in two- and three-dimensional variably saturated soil media).
IHACRES	**I**dentification of unit **H**ydrographs **A**nd **C**omponent flows from **R**ainfall, **E**vaporation and **S**treamflow data	Used to characterise the dynamic relationship between rainfall and streamflow, using rainfall and temperature (or potential evaporation) data, and to predict streamflow.
INCA	**I**ntegrated **N**itrogen in **C**atchments	Process based dynamic model for simulating impacts of change e.g. Climate Change, Land Use change, Pollution changes INCA-N for Hydrology, nitrate-N and Ammonium INCA-P for total P and SRP, and algae INCA-C for carbon INCA-Sed for sediments INCA-Mine representation of plant/soil system and in-stream nitrogen dynamics.
INCA-CHALK	**I**ntegrated **N**itrogen in **C**atchments **CHALK**	Designed for catchment management of nutrient loadings to streams and water movement for abstractions from Cretaceous Chalk aquifers- not relevant to Australian landscapes, no further investigation undertaken
JAMS	**J**ena **A**daptable **M**odelling **S**ystem	Hydrological and solute landscape analysis

Model acronym	Model name	Model purpose
KINEROS	**KIN**ematic runoff and **EROS**ion model	An event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds. Distributed rainfall inputs; each catchment element assigned to a rain gauge from a maximum of 20, rainfall excess, overland flow, channel routing, surface erosion and sediment transport, channel erosion and sediment transport, flow and sediment routing through retention structures.
LUCICAT	**LUCICAT**: *generalised salt and water balance model*	A generalised salt and water balance model, capable of simulating seasonal and episodic events
MAGIC	**M**odel for **A**cidification of **G**roundwater **I**n **C**atchments	Process-oriented intermediate-complexity dynamic model by which long-term trends in soil and water acidification can be reconstructed and predicted at the catchment scale
MATSALU	**MATSALU**	MATSALU is a system of four simulation models for a mesoscale agricultural watershed and the ecosystem of a sea bay. Developed specifically for Matsalu bay, will not be further reviewed.
MCAT	**M**ulti **C**riteria **A**nalysis **T**ool	MCAT is a management tool, rather than a catchment modelling tool. No further review will be undertaken.
MIKE SHE	**MIKE SHE**	Simulate all hydrological domains within the land phase of the hydrological cycle.
MOSS	**MOSS** model	Used to estimate catchment nutrient loads

Model acronym	Model name	Model purpose
NuMASS	**Nu**trient **Ma**nagement decision **S**upport **S**ystem	Used for nutrient amendments and lime application modelling. Diagnoses soil constraints and selects the appropriate management practices, based on agronomic, economic and environmental criteria, for location-specific conditions.
PERFECT	Productivity Erosion Runoff Functions	A biophysical model that simulates the plant-soil-water-management dynamics in an agricultural system. It was developed to simulate the major effects of management and environment and to predict runoff, soil loss, soil water, drainage, crop growth and yield.
RothC	**Roth C**arbon model	Simulates turnover of organic carbon in souls. Calculates total organic carbon, microbial biomass carbon and Δ14C over timescales up to centuries. Originally developed for arable soils, but had now been applied to grasslands and forests.
SedNet	**SedNet**	Regional sediment and nutrient budgets for river networks. Spatially accounts for sediment and nutrient stores, sources and fluxes.
SHETRAN	**S**ystem **H**ydrologique **E**uropeen **TRAN**sport	SHETRAN is a three-dimensional, coupled surface/subsurface, physically-based, spatially-distributed, finite-difference model for coupled water flow, sediment transport and multiple, reactive solute transport in river basins. Gives a detailed description of the flow and transport in the basin, which can be visualized using animated graphical computer displays.

Model acronym	Model name	Model purpose
SMART	**S**imulation **M**odel for **A**cidification's **R**egional **T**rends	A soil acidification model developed to estimate the long term chemical changes in soil and soil water in response to changes in atmospheric deposition.
SOILN	**SOILN**	SoilN module describes the dynamics of both carbon and nitrogen in soil.
STONE	**STONE**	Used to assess the (long term) impact of nutrient management strategies and manure legislation on nitrate concentrations in groundwater and nutrient load of surface water systems on national scale
SWAT-G	**S**oil and **W**ater **A**ssessment **T**ool -**G** modification	Modified version SWAT-G can be used which yields far better results for catchments with predominantly steep slopes and shallow soils over hard rock aquifers.

Model acronym	Daily Time Step	Sub Models	Developer/Owner
2CSalt	Yes, however 2CSalt uses a monthly time-step water balance, derived from	1D Water Balance model, PERFECT	CRC Catchment Hydrology

	multiple runs of daily time-series.		
ANNEX	Yes	HBV hydrological model, SOILN, ICECREAM, USLE	Not identified
ANSWERS	Yes, and 60-second time-step during rainfall		Purdue University in West Lafayette, Indiana
APSIM	Yes	SOILN	Not found
BC2C	No, Annual time step		CSIRO, eWater & Salient Solutions Australia
CASC2D	Information not readily available		
CatchmentSIM	Not applicable		Catchment Simulation Solutions Pty Ltd
CMSS	No, Annual time step		eWater CRC
CREAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.		
DNDC	Yes		Not identified
DRAINMOD	On an hour-by-hour, day-by-day basis	Numerous sub-models and variations of DRAINMOD have been developed http://www.bae.ncsu.edu/soil_water/drainmod/index.html	Dr.Wayne Skaggs at the Department of Biological & Agricultural Engineering, North Carolina State University, Raleigh, NC
DWSM	Storm event; variable constant steps		Not identified
EPIC	This model is incorporated into the SWAT model, therefore no further review undertaken.		
ESWAT	Sub-daily time-step	QUAL2E, SWAT	Not identified
Model acronym	Daily Time Step	Sub Models	Developer/Owner

Felflow	Different time-stepping methods: • constant time steps • varying pre-defined time steps • fully automatic time-stepping procedure using predictor-corrector or aggressive target-based schemes		Water Resources Planning and Systems Research Inc. (WASY GmbH) of Berlin, Germany, which has recently become a part of DHI Group.
GLEAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.		
HBV-NP	Yes	SOILN, ICECREAM	Swedish Water Management Research Programme.
HSPF	Yes	PERLND- previous land, IMPLND- impervious land, RCHRES- streams or mixed reservoirs, Agricultural Runoff Model (ARM) and Non-Point Source (NPS)	U.S. EPA
HYDRUS	Yes, but can vary the temporal scale	CW2D nitrogen module	U.S. Salinity Laboratory in cooperation with the International Groundwater Modeling Center (IGWMC), the University of California Riverside, and PC-Progress
Model acronym	Daily Time Step	Sub Models	Developer/Owner

IHACRES	Can use minute, daily or monthly time steps. Hourly time steps are recommended for catchments up to 1 km2, while a daily time step is appropriate for larger catchments.		Australian National University (ANU) iCam
INCA	Yes	There are several modifications of the INCA model	Prof Whitehead and AERC team at Reading
INCA-CHALK	This model is not appropriate for use in Australia, therefore no further review undertaken.		
JAMS	Yes, but can operate on a finer scale if data is available		Department of Geoinformations, Hydroglogy and Modelling at the University of Jena, Germany.
KINEROS	Variable constant steps depending numerical stability.		USDA ARS Southwest Watershed Research Centre
LUCICAT	Yes		Centre for Water Research, University of Western Australia and Department of Environment, WA.
MAGIC	Yes, but typically operates on seasonal or annual time steps and is implemented on decadal or centennial time scales		Macaulay Land Use Research Institute
MATSALU	Developed specifically for Matsalu bay, will not be further reviewed.		
MCAT	MCAT is a management tool, rather than a catchment modelling tool. No further review provided.		
Model acronym	Daily Time Step	Sub Models	Developer/Owner

MIKE SHE	Yes, Long term and storm event; variable steps depending on numerical stability		European consortium of three organizations: the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute.
MOSS	Unable to access information.		
NuMASS	Not identified	Synthesized from modules covering acidity, phosphorus: Acid Decision Support System (ADSS), Nitrogen Decision Support System (NDSS) and Phosphorus Decision Support (PDSS) and nitrogen.	Collaborative effort of several American universities (University of Hawaii, Cornell, Texas A&M, and North Carolina State University) and the Philippine Rice Research Institute (PhilRice) and the International Rice Research Institute (IRRI) in the Philippines, funded by United States Agency for International Development (USAID).
PERFECT	Yes	Sub-models that simulate soil water balance, crop growth, soil erosion, crop residue and crop cover	National Soil Conservation Program and the Land and Water Resources Research and Development Corporation
RothC	No, monthly time step		Rothhamsted
SedNet	No		eWater CRC, CSIRO Land and Water
Model acronym	Daily Time Step	Sub Models	Developer/Owner

SHETRAN	User defined variable time step	SHE, grid oriented phosphorus component (GOPC)	Water Resources Systems Research Laboratory (WRSRL), developed by international collaboration between groups in the United Kingdom, Denmark, and France
SMART	Not identified		Winnard Staring Centre for Integrated Land, Soil, and Water Research (SC-DLO)
SOILN	Yes		Swedish University of Agricultural Science
STONE	Not identified	STONE model consist of a fertilizer and manure distribution module (CLEAN or MAMBO), an hydrological model (SWAP) and a soil-water quality model (ANIMO)	Not identified
SWAT-G	Yes	AVSWAT (ArcView SWAT), SWIM, SWAT-G, ESWAT, GLEAMS, CREAMS, EPIC, SWRRB, erosion and sediment yield are measured using the MUSLE- modified universal soil loss equation	United States Department of Agriculture, Agricultural Research Service (USDA-ARS)

Model acronym	Primary reference	Peer reviewed	Scale/resolution	Licence/Access
2CSalt	Stenson et al. 2006	Yes	Catchment scale, typically < 2000 km2	Requires subscription. http://www.toolkit.net.au/Tools/Default.aspx
ANNEX	Not found	Yes	1 km2 to more than 1	Cannot currently locate

			000 000 km2	
ANSWERS	Beasley et al. 1978	Yes	Model uses cell sizes up to 1ha, and can model catchments ≤300 km	Cannot currently locate
APSIM	Not found	Yes	Not found	Licence required to download software package http://www.apsim.info/apsim/Downloads/default.asp
BC2C	Dawes et al. 2004	Yes	Catchment or sub-catchment scale, 1000 – 50 000 km2	No licence fee, but must be a Catchment Modelling Toolkit member to download software www.toolkit.net.au/bc2c
CASC2D	Julien et al. 1995	Yes	Catchment scale	Cannot currently locate
CatchmentSIM	http://www.csse.com.au	Yes	Sub-catchment	License and heavy costs involved
CMSS	Davis et al. (1991), www.toolkit.net.au/cmss	Yes	Sub-catchment scale	No licence fee. Download at http://www.toolkit.net.au/Tools/CMSS/downloads
CREAMS	Knisel, 1982	Yes	Catchment	Incorporated into SWAT, thus free access.
DNDC	Li et al. 1992	Yes	Sub-catchment	Free access http://www.dndc.sr.unh.edu/index.html
Model acronym	Primary reference	Peer reviewed	Scale/resolution	Licence/Access
DRAINMOD	Breve, 1994	Yes	Field and catchment scale	Free access http://www.bae.ncsu.edu/soil_water/drainmod/download.html

DWSM	Borah et al., 2002; Borah and Bera, 2003	Yes	Catchment: sizes ranging from few acres to several hundred square kilometres	Availability: Non-Proprietary Cost: Free
EPIC	Williams et al. 1983	Yes	Catchment	Incorporated into SWAT, thus free access.
ESWAT	Van Grienscen & Bauwens, 2005	Yes	Catchment	Free access
Felflow	DHI-WASY	Yes	Broad range of small-scale and large-scale application capabilities	Requires a license key. It is a proprietary code and not freely available. Heavy costs for licence and access http://www.feflow.info/service.html
GLEAMS	Leonard et al., 1987	Yes	Catchment	Incorporated into SWAT, thus free access.
HBV-NP	Arheimer and Brandt, 2000	Yes	1 km^2 to > 1 000 000 km^2	Could not locate
HSPF	Bicknell et al., 1993	Yes	Catchment	This product is no longer commercially available, however it can still be downloaded for free http://www.scisoftware.com/products/hspf_model_details/hspf_model_details.html
HYDRUS	Šimůnek et al., 2008	Yes	Catchment and sub-catchment	Fees and licences required
IHACRES	Jakeman et al. (1990); Jakeman et al. (1993)	Yes	1 ha experimental catchments to 100,000 km^2 catchments	Free access http://www.toolkit.net.au/ihacres)
INCA	Whitehead et al., 1998	Yes	Catchment	The INCA model is available FREE of charge for evaluation purposes from the AERC website. http://www.reading.ac.uk/SHES/
INCA-CHALK	No further review undertaken due to inapplicability to Australian landscapes.			
Model acronym	Primary reference	Peer reviewed	Scale/resolution	Licence/Access
JAMS	Kralisch and Krause, 2006	Yes	Catchment and sub-catchment	Free access http://jams.uni-jena.de
KINEROS	Woolhiser et al. 1990;	Yes	Small catchments only	Free access, no licence required

	Smith et al. 1995			http://www.tucson.ars.ag.gov/kineros/
LUCICAT	Bari and Smettem, 2004; Bari et al. 2003	Yes	Catchment and sub-catchment	Not located
MAGIC	Cosby et al., 1985	Yes	Catchment	Not located
MATSALU	No further review undertaken due to inapplicability to Australian landscapes.			
MCAT	No further review undertaken			
MIKE SHE	Refsgaard and Storm, 1995	Yes	Catchment and local scale	Not located, however includes costs
MOSS	Moss et al., 1993	Yes	Catchment scale	Not located
NuMASS	Osmond et al., 2002	Yes	Catchment and sub-catchment	Free to download http://www.soil.ncsu.edu/scripts/numass/download.php
PERFECT	Littleboy et al. 1989 re-released 1993	Yes	It is only applicable for field-sized areas	Not found
RothC	Coleman and Jenkinson, 1999	Yes	Mostly used in field studies, can be used on larger scales	Not found
SedNet	Prosser et al 2001, www.toolkit.net.au/tools/sednet	Yes	Sub-catchment/ regional scale, 3,000 - 1,000,000 km2	Free download and licence http://www.toolkit.net.au/Tools/Download/Default.aspx?id=1000013
SHETRAN	Ewen et al., 2000 Version 4 SHETRAN	Yes	1 km^2 to 2500 km^2	Requires registration. Download available from http://www.ceg.ncl.ac.uk/shetran/
SMART	Posch et al., 1993	Yes	Catchment scale	Not located
SOILN	Johnsson et al., 1987	Yes	Variety of spatial scales	Not located
STONE	Wolf et al., 2003	Yes	National scale, STONE is also suitable for regional analyses.	Not located
SWAT-G	Eckhardt et al., 2002	Yes	Catchment scale, up to 25,000 km2	Free access

Model acronym	Nitrogen	Phosphorus	Sediments	Surface water	Groundwater	Pesticides	Climate
2CSalt	✗	✗	✗	✓	✓	✗	✗
ANNEX	✓	✓	✓	✓	✓	✗	✓
ANSWERS	✓	✓	✓	✓	✗	✗	✗

APSIM	✓	✓	✓	✓	✗	✗	✗
BC2C	✗	✗	✗	✓	✓	✗	✗
CASC2D	✗	✗	✓	✓	✗	✗	✗
CatchmentSIM	✗	✗	✗	✗	✗	✗	✗
CMSS	✓	✓	✓	✓	✗	✗	✓
CREAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.						
DNDC	✓	✗	✗	✗	✗	✗	✗
DRAINMOD	✓	✗	✓	✗	✗	✗	✓
DWSM	✓	✓	✓	✓	✓	✓	✗
EPIC	This model is incorporated into the SWAT model, therefore no further review undertaken.						
ESWAT	✓	✓	✓	✓	✓	✓	✓
Felflow	✗ not specifically	✗ not specifically	✓	✓	✓	✗	✗
GLEAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.						
HBV-NP	✓	✓	✓	✓	✓	✗	✗
HSPF	✓	✓	✓	✓	✗	✓	✗
HYDRUS	✓	✓	✓	✓	✗	✓	✗
IHACRES	✗	✗	✗	✓	✓	✗	✗
INCA	✓	✓	✓	✓	✓	✗	✓
INCA-CHALK	Not relevant to Australian landscapes, no further investigation undertaken						
JAMS	✓	✓	✗	✓	✓	✓	✗
KINEROS	✗	✗	✓	✓	✗	✗	✗
LUCICAT	✗	✗	✗	✓	✓	✗	✗
MAGIC	✓	✗	✓	✓	✓	✗	✗
MATSALU	Developed specifically for Matsalu bay, will not be further reviewed.						
MCAT	No further review undertaken						
MIKE SHE	✓	✗	✓	✗	✓	✓	✗
MOSS	✓	✓	✓	Not found	Not found	Not found	✗
Model acronym	Nitrogen	Phosphorus	Sediments	Surface water	Groundwater	Pesticides	Climate
NuMASS	✓	✓	✓	✗	✗	✗	✗
PERFECT	✗	✗	✗	✗	✓	✗	✗
RothC	✗	✗	✗	✓	✗	✗	✗

SedNet	✓	✓	✓	✓	✓	✗	✗
SHETRAN	✓	✓	✓	✓	✓	✗	✗
SMART	✓	✗	✗	✗	✗	✗	✗
SOILN	✓	✓	✓	✓	✓	✗	✗
STONE	✓	✓	✗	✗	✓	✓	✗
SWAT-G	✓	✓	✓	✓	✓	✓	✓

Model acronym	Limitations	Benefits
2CSalt	Requires large data inputs, 2CSalt requires calibration against streamflow and stream electrical conductivity data at the catchment outlet.	Computationally intensive. Access to a broader range on land-use options, providing output to examine seasonal impacts, the ability to calibrate to measured gauged data, and output which can feed into river routing models.

ANNEX	ANNEX model estimates are based on the Australian Soil Resource Information System database of nutrient concentrations in soils, which can lead to overestimation in some climates. This database may need refinement.	Speciates dissolved nutrients into organic and inorganic forms.
ANSWERS	Cannot be used to predict gully erosion, limiting usefulness in Australia. Does not always satisfactorily predict storm runoff due to its poor representation of the infiltration processes	Performs well for predicting soil loss. ANSWERS is a continuous simulation model, useful for analysing long-term effects of hydrological changes and catchment management practices, especially agricultural practices.
APSIM	Modelling capabilities of APSIM are heavily influenced by data availability. If insufficient data is available the model will not produce adequate outputs	Includes extensive soil and plant management modules, and has been applied and validated extensively for many crops. Crop models are being incorporated into the model framework.
Model acronym	Limitations	Benefits
BC2C	Operates on an annual time step. Catchments should be unregulated. Does not predict daily/monthly/annual changes in water and salt balance, uses long-term average values. BC2C is intended for local-upland catchments areas where groundwater flow lengths are typically less	Fast to run, and designed to be simple to use by a range of people. BC2C can be run with a user-friendly interface that allows changes to surface vegetation to be reflected in water and salt yield over time. It readily allows a user to get a feel for the current situation in terms of water and salt

	than 10 km. BC2C uses simple and representative groundwater properties, and while it operates at a single GFS (Ground Flow Systems) scale, its results should be aggregated to a whole-of-catchment level. Requires knowledge of the processes affecting the flow of water through catchments, along with some supporting data to assist in fitting the model.	yield, and the relative differences that can be made by changing the percentage of tree cover within individual sub-catchments of the catchment. It is a simple model that can be used to model salinity effectively.
CASC2D	Outputs are typically limited to discharge hydrographs	Produces time series maps of spatial outputs, maps can easily display temporal and spatial variations
CatchmentSIM	Hydrologically focused model. Requires extensive training in GIS for effective model use. Is used to generate and delineate sub-catchment boundaries and create raster file based imagery, not model catchment dynamics.	Large amount of instructional information and easy to understand tutorials are available from the website www.csse.com.au
Model acronym	Limitations	Benefits
CMSS	CMSS does not consider hydrology or any time-variant components so is restricted to long-term average behaviour. CMSS predicts average annual loads. Rainfall-runoff or infiltration is not modelled. Nutrient loads can be overestimated when the model is applied to large catchments.	Not complex, designed for use by people without a high level of computational expertise. Requires minimal inputs: land use, annual nutrient generation rates for the catchment, simple data on proposed management practises.

CREAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.	
DNDC	DNDC is mainly run with a simulation depth of 30 cm, which is not sufficient to estimate site scale denitrification in the soil column	Can be effectively coupled with a hydrological model
DRAINMOD	The model is not readily applicable to daily water management in Australian soils since it requires extensive soil and climate data, which are normally not available.	The model has been successfully tested and applied in wide variety of geographical and soils conditions. The latest version DRAINMOD 6.0 combines the original hydrology model with a nitrogen sub-model and a salinity sub-model.
EPIC	This model is incorporated into the SWAT model, therefore no further review undertaken.	
ESWAT	Requires a large amount of detailed input data.	Incorporates a detailed river water quality module. An hourly time step is used for the simulation of water, nutrients, pesticides and river quality processes. The simulation of erosion processes is performed at a user-defined fraction of an hour and requires precipitation data with a sub-hourly time step. Includes a multi-objective calibration module that can be applied for multi-site and/or multi-variable calibrations
Model acronym	Limitations	Benefits

Felflow	Used for a number of years in industry and Universities. Can conform to complex boundaries. Hydro-geologic parameters are averaged across an element. Data entry into the software package is difficult (not user friendly).	Unstructured meshing, thus much better representation of features like rivers, fractures, water well locations by adaptation of the mesh. Less computational effort due to reduced element numbers for large regional models. Broad range of small-scale and large-scale applications
GLEAMS	This model is incorporated into the SWAT model, therefore no further review undertaken.	
HBV-NP	Has only been extensively used and calibrated in Sweden.	Process-based, semi-distributed conceptual model
HSPF	Surface water focused. Due to its conceptualization of the overland (sub-basin) areas as leveled detention storage and use of the storage-based or nonlinear flow equations in routings, HSPF is not adequate for simulating intense single-event storms, especially for large sub-basins and long channels. It is unable to represent single-event flood waves.	HSPF is a continuous simulation model, useful for analysing long-term effects of hydrological changes and catchment management practices, especially agricultural practices. HSPF is capable of simulating urban and suburban land uses as well. HSPF can run on a time step smaller than a day, and can thus be used to model storm events.
HYDRUS	Does not model climate or impact of pesticides.	Incorporates conservative and non-conservative solutes, has options for dual permeability, 3-D transport and groundwater. Provides an attractive graphical user interface. Is able to account for and simulate with a high degree of spatial and temporal flexibility.
Model acronym	Limitations	Benefits

IHACRES	Focuses on streamflow and rainfall	Uses a non-linear loss module to calculate the effective rainfall and a linear routing module to convert effective rainfall into streamflow, The new module has only 3 parameters and has significantly less correlation between the parameters.
INCA	Does not have the ability to model runoff for the Australian climate currently.	Has successfully been applied in both European countries and tropical and sub-tropical regions e.g. Brazil
INCA-CHALK	Not relevant to Australian landscapes, no further investigation undertaken	
JAMS	Requires lots of training to use the program, and requires detailed data inputs	Can model flexibly on different spatial and temporal scales. Can be custom-tailored with the user defining the modules to be used for particular application
KINEROS	Only considers water movement and balance.	Excellent erosion and sediment transport models. Free source code and access. Can be used to determine the effects of disturbance such as urban development. Account for lateral movement of water and solutes in the soil profile.
LUCICAT	Currently only applicable to gauged catchments as parameter estimation relies on matching measured streamflow and salt load data. Model requires minimal calibration as most variables remain 'fixed' based on previous catchment studies.	6 key parameters based on topography, land use and soils to describe the catchment and accounts for land use management through spatial assignment of time series and leaf area development and rooting-depths.
MAGIC	The modelled output is insensitive to depositional and flow routing changes, indicating that catchment processes are not being represented to a sufficient degree.	MAGIC produces long-term reconstructions and predictions of soil and stream water chemistry in response to scenarios of acid deposition and land use.
MATSALU	Not relevant to Australian landscapes, no further investigation undertaken	
MCAT	Not a modelling tool, no further investigation undertaken	
Model acronym	Limitations	Benefits

MIKE SHE	Expensive and requires long computational periods for simulation to take place	Spatially distributed model. Allows each hydrological process to be modelled at a different spatial and temporal scale if required
MOSS	Cannot access information readily.	Locally calibrated. Uses flow-dependent generation rates for each land use type to estimate catchment loads
NuMASS	Does not consider well the interactions between nutrients	An advantage of a conceptual model is that it goes from the particular to the general, and can be analysed both deterministically and stochastically.
PERFECT	Nutrient modelling is restricted to crop-growth. It is a one-dimensional model that simulates a single point in a landscape and does not consider partial area runoff processes or lateral movement of water. It is only applicable for field-sized areas with homogeneous soils, topography and climate.	Input data readily available. Cropping systems model that contains dynamic water balance, crop growth, soil erosion, fallow management and planting decision sub-models in an integrated framework
RothC	Functions on a monthly time step and only models C	This approach has the advantage of allowing the model to be initialised at any point in the landscape without the necessity for historical data or for using the model itself to generate an initial equilibrium pool structure. The correct prediction of the changing total soil organic carbon levels, as well as the pool structure over time, acts as an internal verification and gives confidence that the model is performing as intended
Model acronym	Limitations	Benefits

SedNet	Daily time steps can be disaggregated, although the developers recommend that this would need careful validation.	SedNet explicitly represents supply processes (hillslope, gully riverbank erosion, diffuse and point nutrient supply) to assist targeting of specific management measures. Represents floodplain and reservoir deposition, important for assessing delivery to the catchment outlet. The effects of temporal variability in climate and stream flow etc. are integrated to predict material budgets. Budgets can be compared with "natural" conditions. Models both suspended and bed-load sediment movement. The ANNEX (Annual Network Nutrient EXport) module divideds dissolved nutrients into organic and inorganic forms.
SHETRAN	Focuses on water flow, solute and sediment transport in river catchments. Requires heavy computational requirements and is complex to use, and lengthy training is required to successfully use the model.	Physically-based, spatially-distributed modelling systems have particular advantages for the study of basin change impacts and applications to basins with limited records.
SMART	Very few biological processes are taken into account; SMART does not incorporate site abiotic factors and does not account for all nitrogen processes.	Processes included in the model: weathering, cation exchange, sulphate absorption
SOILN	Plant growth is assumed not to be limited by nutrient availability	
STONE	Insufficient data available	
Model acronym	Limitations	Benefits

SWAT-G	Requires a large amount of detailed input data.	Includes modifications concerning the regionalisation of precipitation and temperature, the calculation of the evapotranspiration, the generation of surface and sub-surface runoff, the simulation of plant growth and crop rotation, as well as a new option for the control of reservoirs.

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