UNIVERSITY OF SOUTHERN QUEENSLAND

# MODELLING HERBICIDE MOVEMENT FROM FARM TO CATCHMENT USING THE SWAT MODEL

A Dissertation submitted by

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## CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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Signature of Candidate Date

ENDORSEMENT

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Signature of Supervisor Date

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## ABSTRACT

Water quality in Australia's northern grains farming areas often exceeds water quality trigger values for suspended sediments, nutrients and some herbicides (CBWC, 1999). While there are many land uses in these areas that contribute to the resultant water quality, of particular concern for the grains farming industry is the widespread detection in rivers of chemicals used by their industry, namely atrazine and metolachlor. A comparison of Hodgson Creek catchment (South East Queensland, Australia) herbicide data with national water quality guidelines shows that trigger values are frequently exceeded.

That water quality trigger values are exceeded is expected for a highly modified catchment such as Hodgson Creek, and the Australian New Zealand Environment and Conservation Council (ANZECC) (2000) guidelines make provision that in such catchments, locally derived targets should be set. Natural resource managers therefore require skills in linking planned management with their ability to set or meet targets.

The opportunity suggested itself for using catchment modelling to set realistic targets for water quality based on the adoption of best management farming practices. This study investigated the suitability of the Soil and Water Assessment Tool (SWAT) to fulfil this modelling role in an Australian context of land use management. To test the suitability of SWAT to fulfil this role, the study aimed to determine the feasibility of using the model to explicitly depict farm management practices at a paddock scale to estimate resultant catchment water quality outcomes.

SWAT operates as two distinct sub-models. A hydrologic response unit (HRU) (the paddock scale model) generates runoff and constituents, and the output of many HRU are summed and routed through a stream network. The method for calibration of SWAT proposed in the user manual (Neitsch *et al.*, 2001) is to calibrate against streamflow before calibrating sediment and then herbicides. The logic of testing in a process dependent order is sensible, however the method proposed by Neitsch *et al.* (2001) assumes that the HRU processes are reliable and

calibration only need consider catchment scale processes. A review of the literature suggested that there had been limited testing of HRU process in studies where SWAT had been applied.

Data available for model testing came from both paddock and catchment studies. The effects of cultivation management practices on runoff and erosion have been well characterised for the study area by Freebairn and Wockner (1996). Atrazine dissipation in soil and loss in runoff was available from a study of a commercial farm in the Hodgson Creek catchment (Rattray *et al*, 2007). An ambient and event based water quality monitoring for suspended sediments and herbicides provided data for the Hodgson Creek catchment for the period 1999 to 2004 (Rattray, unpublished data).

The model required minimal calibration to achieve good predictions of crop yields and surface cover for winter crops. However, testing of summer cropping component revealed structural problems in SWAT associated with the end of a calendar year. Testing also revealed that perennial pastures and trees are modelled with unrealistic fluctuations in biomass and leaf area index.

The model was able to represent hydrology well across a range of scales (1-50,000 ha). Catchment scale runoff data was well matched for a range of tillage treatments. The model was found to be able to attain a good prediction of monthly runoff at the catchment scale. This is consistent with the finding of most other SWAT studies.

The model was able to represent average annual erosion reasonably well using the Universal Soil Loss Equation (USLE) when tested at the HRU scale (1 ha) against a range of tillage management data. When tested at the catchment scale the model was found to be able to match average annual sediment loads for the catchment however annual variability in sediment loads was poorly matched.

Testing of the herbicide model for SWAT found that model compared poorly with paddock scale trial data. The reason for poor model performance can be attributed to an inadequate representation of processes and model output was unrealistic compared to our understanding of herbicide transport processes. When the model was tested at a catchment scale it was found to compare very poorly with catchment scale observations. This can be explained in part by the deficiencies of the HRU herbicide model, but is also due in part to difficulties in parameterisation of spatial and temporal inputs at the catchment scale.

While SWAT provides a model with detailed physical processes, the capacity to apply the model is let down by an ability to practically determine the spatial and temporal extent of the farming practices (i.e. where and when are tillage and herbicides applied in the catchment). The challenge to applying SWAT is that farming practices in Australia vary markedly from year to year. SWAT requires the user to input crop practices in as a fixed rotation while Australia's highly variable climate with unreliable seasonal weather patterns results in opportunistic farming practices. Hence this is a major limitation in the models ability to predict catchment outcomes, particularly for herbicides where off site losses are highly dependant on application timing. In attempting to validate herbicide losses at the whole of catchment scale it became apparent that uncertainty in the temporal variation of farm operations within the catchment poses a major limitation to accurately reproducing observations at the catchment outlet.

It is concluded that that there is limited usefulness of SWAT for investigating the impacts of land management on catchment scale herbicide transport for Australian conditions.

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# CHAPTER 1. INTRODUCTION

## 1.1. STUDY AIM AND OBJECTIVES

The aim of this study was to determine if a model could be used to calculate the effect of farm management practices on the transport of herbicides at catchment scale. A model, in this context, takes the form of a mathematical representation of water balance, erosion and herbicide processes implemented in a computer program. The study aimed to establish the feasibility of using such a model to depict farm management practices at paddock scale explicitly, estimate the losses of herbicides from paddock scale and estimate resultant catchment water quality outcomes.

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 2001; Neitsch *et al.*, 2001) was selected to investigate herbicide movement within the Hodgson Creek catchment, an upland sub-catchment of the Condamine-Balonne catchment in South-East Queensland, Australia. SWAT is a catchment model developed to predict the impact of land management practices on water balance, erosion, and in-stream routing of runoff, sediment, and agricultural chemical. Developed by the United States Department of Agriculture (USDA), SWAT is reported to be suitable for herbicide transport studies (Santhi *et al.*, 2001).

The objectives of this study were to determine the suitability of SWAT:

1. To represent processes important in predicting generation and routing of runoff, suspended sediment, and herbicide at both paddock and catchment scale; and
2. As a tool for use in water quality assessment and planning processes.

To assess the suitability of SWAT to model hydrology, erosion and herbicide transport for Australian conditions a number of model processes important to model predictive performance were tested against observed data. SWAT was tested for its ability to correspond with observed data from both paddock (1-5 ha) and catchment (50,000 ha) data. Consideration was given to how SWAT fits with the needs of water quality target setting and assessment in Australia for herbicide contamination of surface water.

## 1.2. A NEED FOR A PROCESS TO INTEGRATE PADDOCK MANAGEMENT INTO CATCHMENT WATER QUALITY ASSESSMENT

### 1.2.1. Water quality guidelines for environmental protection

Water quality in Australia's northern grains farming areas often exceed water quality trigger values for suspended sediments, nutrients and some herbicides (CBWC, 1999). While there are many land uses in these areas that contribute to poor water quality, of particular concern for the grains farming industry is widespread detection in rivers of chemicals used by this industry, namely atrazine and metolachlor. Consistent detection of these chemicals in town water supply sources has occurred in the Darling Downs region of South East Queensland. Monitoring over a 5-year period (1997-2001) of town water supplies in the Condamine River catchment resulted in detection of residues (>0.05 µg/l) of atrazine in ninety percent of samples and metolachlor in eighty percent of samples (CBWC, 2001).

The Australian and New Zealand Environment and Conservation Council (ANZECC) (2000) Guidelines for Water Quality define trigger values for a range of physical and chemical water quality parameters. Importantly, a trigger value is not a target, but a conservative threshold that if exceeded may indicate possible water quality contamination. There are a number of trigger values for each water quality parameter to reflect the many uses of water, including: industrial, recreational, agricultural, human consumption, and aquatic ecosystems. In this study, trigger values for aquatic ecosystems and human consumption were considered.

The ANZECC (2000) guidelines state that when a water quality parameter exceeds a trigger value that this should set in motion an investigation to set a locally relevant target for the parameter, and subsequently actions to achieve the target. The guidelines outline a method to derive a locally relevant target based on ambient monitoring of a reference site in a well-preserved catchment. The guidelines also suggest that a modelling framework could provide a suitable method for target setting of water quality to take account of local environmental conditions, but do not suggest a specific model or method. Neither do the guidelines suggest a method to determine what actions would be required to move from the current water quality state to meet a target.

### Comparison of water quality in the Hodgson Creek catchment with ANZECC trigger values

A 6-year monitoring program at the Hodgson Creek Gauging Station (G.S.) (see Appendix A, Map 1) collected data on a range of physical and chemical water quality parameters (Rattray, unpublished data). Median values for suspended sediment and turbidity are shown in Table 1 and compared with triggers values from ANZECC (2000) and CBWC (2002) guidelines for protection of aquatic ecosystems. Median values considerably exceed trigger values in both cases.

**Table 1 : Trigger values for protection of aquatic ecosystems (ANZECC, 2000)[1] and (CBWC, 2002)[2] and observed median values for the Hodgson Creek G.S.**

| | Trigger value (Aquatic ecosystems) | Median values (1999-2005) |
|---|---|---|
| **Suspended sediments[1] (mg/l)** | 11 | 487 (n= 55) |
| **Turbidity[2] (ntu)** | 2-25 | 47 (n= 68) |

Herbicide trigger values for human health from the National Health and Medical Research Council (NHMRC) Australian Drinking Water Guidelines (ADWG) (NHMRC, 2004) are presented in Table 2. The definition of a guideline value and health value are given below Table 2. Maximum observed concentrations from monitoring at the Hodgson Creek G.S. exceed the guideline values but do not exceed the health values.

**Table 2 : Trigger level values for atrazine and metolachlor for human health (NHMRC, 2004) and maximum observed values at Hodgson Creek G.S. (Rattray, unpublished data).**

| | Guideline value | Health value | Maximum values (1999-2005) |
|---|---|---|---|
| **Atrazine (µg/L)** | 0.1 | 40.0 | 8.3 (n= 74) |
| **Metolachlor (µg/L)** | 2.0 | 300.0 | 5.0 (n= 47) |

*"Guideline values* – set at or about the limit of determination (LOD). This value is the level at which the pesticide can be reliably detected using practicable, readily available, validated analytical methods. Where a pesticide is approved for use in water or water catchment areas, the guideline value is set at a level that is consistent with good water management practice and that would not result in any significant risk to the health of the consumer over a lifetime of consumption. **If a pesticide is detected at or above the guideline value, steps should be taken to determine the source and to stop further contamination**. Exceeding the guideline value indicates that undesirable contamination of drinking water has occurred; it does not necessarily indicate a hazard to public health.

*Health values* - These values are intended for use by health authorities in managing the health risks associated with inadvertent exposure, such as a spill or misuse of a pesticide.
The values are derived from the acceptable daily intake (ADI) and set at about 10 per cent of the ADI for an adult weight of 70 kg for a daily water consumption of 2 litres. The health values are very conservative, include a range of safety factors and always err on the side of safety."
**Source: NHMRC, 2004.**

Ranges of trigger levels are given for herbicides for the protection of aquatic ecosystems from 99% down to 80% of species (ANZECC, 2000). Trigger levels for atrazine are shown in Table 3. There are no trigger levels for metolachlor due to insufficient to set triggers (ANZECC, 2000).

The maximum observed atrazine concentration from Hodgson Creek G.S. of 8.3*µg/l*, (Table 2) exceeds the 99% trigger but not the 95% trigger. This indicates that less than 5% of species in aquatic ecosystems are at risk from atrazine impacts at this location. It is worth considering however that no account is taken in the guideline as to the cumulative influence of multiple pollutants on aquatic ecosystems.

**Table 3 : Trigger level values for protection of aquatic ecosystems (ANZECC, 2000). The maximum observed values for the Hodgson Creek G.S. (1999-2005) was 8.3 μg/L (n=74) (Rattray, unpublished data).**

| Level of protection (% of species) | 99% | 95% | 90% | 80% |
|---|---|---|---|---|
| **Atrazine (μg/l)** | 0.7 | 13 | 45 | 150 |

The comparison of observed water quality from Hodgson Creek with human health and aquatic ecosystems guideline values establishes that trigger values for suspended sediment, turbidity, and atrazine are exceeded. This is consistent with the regional findings by CWBC (2001) for town water supplies in the Condamine River and according to ANZECC (2000) establishes the need to determine locally relevant water quality targets for these parameters.

#### 1.2.2. A need for a process to assess water quality outcomes of paddock management

Atrazine and metolachlor are important chemicals in summer grains farming, particularly in sorghum cropping, where they assist in reducing weed pressure (QDPI, 2002). This can assist in increasing crop yields and make these farming systems more economically viable (QDPI, 2002).

Findings by the CBWC (2001) that atrazine and metolachlor have been measured in town water supply sources above water quality trigger levels is of concern to both water users, and to farming industries that who may face reduced access to these chemicals. This has lead to pressure within the farming industry to increase the adoption of farming best management practices (BMP), in the hope that this will lead to improvements in water quality and a reduction in chemical detections.

However, there is a great amount of uncertainty regarding the link between BMP adoption and the level of herbicides found in streams. The question regards what changes at catchment scale could be expected given widespread adoption of BMP at the paddock scale. In Australia there has been little work to date that has tried to link on-farm practices of land managers with catchment scale herbicide movement. Such a process has the potential to allow policy makers to understand the impact that the adoption of BMP will have on catchment outcomes.

Understanding the outcome that could be achieved from adoption of BMP could be useful from two perspectives. Firstly it could be used to understand what a realistic targets for suspended sediment and herbicides would be based on adoption of farming BMP. Alternatively it could provide information on what level of adoption of practices would be required to meet a water quality target set by another means.

In a highly variable climate such as Australia where a large variation in annual rainfall and runoff occurs, the use of a model that incorporates long term climate records would appear to provide considerable benefits to policy makers in setting targets. The ANZECC (2000) guidelines suggest that a modelling framework could provide a suitable method for target setting of water quality to take account of local environmental conditions, but make no suggestion of a specific model or method.

The opportunity therefore suggests itself for the use of a catchment modelling approach to inform the water quality target setting process. This study investigates if the SWAT model is able to adequately link paddock scale and catchment scale water quality outcomes adequately.

# CHAPTER 2. LITERATURE REVIEW

## 2.1. SELECTING A MODEL FOR THIS STUDY

### 2.1.1. General approaches to catchment modelling

A review of hydrology and erosion models by Merritt *et al.* (2003) used three major attributes to classify model; namely process description, model structure and temporal scale. They suggest that these are the main features to be considered when choosing a catchment scale models.

**Process description**

Models can be grouped in three main process categories based on the way in which catchment processes are simulated; they are empirical, conceptual or physical. The distinction between these categories is not always clear and can be somewhat subjective and models frequently contain components from more than one category.

Empirical models are based on an analysis of observations to characterise catchment response. Conceptual models are typically based on a representation of the catchment as a series of internal storages linked by transfer flow paths, to give a general description of catchment processes without giving specific details of process interactions. Physical models are based on the solution of fundamental physical equations describing the catchment.

While we expect to have to calibrate parameters for empirical and conceptual models, in theory the parameters of physical models are measurable and so are “known”. In practice however it is often not possible to measure all of the parameters that are needed for a physical model and hence parameters are often still calibrated.

**Model structure**

Catchment models can be grouped by the way in which they represent catchment heterogeneity. That is, whether a model considers processes and parameters to be lumped or distributed.

Distributed models reflect spatial variability of the processes and outputs in the catchments and typically divide a catchment into a grid of cells with computations occurring in each cell. The model output from each cell is routed through a system to the outlet. Semi-distributed models often break the catchment into sub-catchments but ignore spatial distribution of response units within a sub-catchment. Lumped models do not consider spatial variability within a catchment and apply a single set of parameters to an entire catchment.

**Temporal resolution**

Temporal resolution refers to the time step increment used for modelling catchment processes. Choosing correct temporal resolution for a modelling experiment is important and making the right choice depends on both data requirements and user needs.

Some empirical models aim to represent long term average response of a system and provide no information on system response for any shorter period. A notable example is the Universal Soil Loss Equation (USLE) that estimates long term average annual erosion, but does not provide information on discreet time intervals.

A time step approach, sometimes called continuous time steps (Merritt *et al.*, 2003), describes system dynamics through time. Many continuous models used in environmental modelling use a daily time step, as this is generally the time step that basic input data such as temperature and rainfall is available at. In some cases shorter time steps are required, such as in hydraulic modelling studies for flood estimation. These event based models aim to predict the response of single hydrologic events, such as a single storm, and use time steps as short as minutes.

### 2.1.2. Previous pesticide and bio-physical modelling of the study area

**Pesticide modelling**

While there are many models that deal with catchment scale water quality as summarise by Merritt *et al.* (2003), few deal with herbicides. In looking for a model for this study, model choice was influenced heavily by previous studies of water quality for the study region and available modelling expertise.

SKM (2001) used the Pesticide Impact Ranking Index (PIRI) (Kookana *et al.*, 2005) model in their study of pesticide usage in the Upper Condamine catchment. PIRI, a lumped conceptual model approach indicates relative risk of chemical contamination impacts to both surface and groundwater of a catchment. This study identified atrazine as high risk of contaminating surface water and a number of management actions were suggested. PIRI does not allow farm management practices to be modelled explicitly and does not attempt to quantify the impact of management options on catchment response, rather the outcome is provided as a qualitative description.

Further work by the CBWC in 2002 considered costs of adoption of "best practices" to improve water quality. This study defined the cost associated with practice change but gave no estimates of change in water quality that was likely to flow from this investment.

**Bio-physical modelling**

Bio-physical models have been extremely popular within the Darling Downs region and a number of such models have previously been applied to the Hodgson Creek catchment area. Previous work has focussed primarily on paddock scale trials (Silburn and Freebairn, 1992; Littleboy *et al.*, 1992a).

Silburn and Freebairn (1992) demonstrated that the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980) was able to represent the hydrology of Vertosols of the Darling Downs. At the paddock scale they were able to achieve good prediction of soil moisture dynamics and described more than 90% of the variability of monthly and annual runoff for three different tillage management systems. They concluded that the model was adequate for practical application of hydrology in the region.

The approach was considered so successful that it led to the development of the Productivity, Erosion Functions for Evaluating the Effects of Conservation Tillage

(PERFECT) model (Littleboy *et al.*, 1992a). This model was based on CREAMS but was unique in its ability to explicitly deal with tillage management and the impact of erosion on long term agricultural productivity. The PERFECT model has been successful in describing the effects of conservation tillage and land management on long term productivity of soils in Australia (Littleboy *et al.*, 1992b; Silburn *et al.*, 1992; Thomas *et al*., 1992; Thomas *et al*., 1995; Abbs and Littleboy, 1998).

During the 1990s in Queensland's and New South Wales cotton growing regions, which includes the study area, the issue of pesticides as a water quality contaminant led to considerable attention being focussed on the cotton industry. The cotton industry responded by investing in research and development of best management practices to reduce the loss of pesticides from cotton farms. As part of this program Connolly *et al.* (2001) used the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard *et al.*, 1987) to compare management options for irrigated cotton to reduce endosulfan transport in the Emerald irrigation area. This study recommended farming practices changes in ranked order of their ability to reduce off site movement of endosulfan from paddocks based on quantitative modelling results.

### 2.1.3. Practical issues for selecting the SWAT model for this study

Two key factors affected model choice for this study; these were compatibility with a specific water quality issue, and scale of application. The required model had to explicitly deal with herbicide generation and transport, and be able to incorporate paddock scale management for predicting outcomes at catchment scale.

The success of the physical based models such as CREAMS, GLEAMS and PERFECT for exploring paddock scale issues in the region meant that when the Geographical Information System (GIS) interface version of SWAT2000 (Neitsch *et al.*, 2001) (referred to as SWAT in this study) was released, considerable interest was shown in its potential applications by the scientific community in the region. The opportunity existed to apply a similar approach to that previously taken with bio-physical models but at larger scales. This interest was clearly demonstrated when over 20 scientists attended a workshop by Susan Neitsch, of the USDA, in Brisbane in 2001.

On the basis of the model selection criteria, that the required model had to explicitly deal with herbicide generation and transport and had to be able to incorporate paddock scale management for predicting outcomes at catchment scale, and a history of applying bio-physical models of similar lineage in the region, SWAT appeared well suited to this study. It operated across the necessary range of scales (1 - 50,000 ha) and contained a herbicide sub-model, and as SWAT grew directly out of the CREAMS model and incorporates the pesticide fate components of GLEAMS (Neitsch *et al.*, 2001), many of its components had been demonstrated to work locally.

The challenge in this study was to apply SWAT in Australian catchment condition. No instances were found in the literature where SWAT had been applied for herbicide generation and transport at a catchment scale in Australia.

## 2.2. OVERVIEW OF THE SOIL AND WATER ASSESSMENT TOOL

The Soil and Water Assessment Tool (SWAT) was developed by the USDA (Arnold *et al.*, 2001; Neitsch *et al.*, 2001) to predict the impacts of land management on water, sediment and agricultural chemical yields in large catchments. It is designed to evaluate likely long term impacts of land use and management changes. SWAT simulates physical processes of plant growth, hydrology, erosion and pesticide transport using soils, land use, climate and topography as primary inputs. SWAT can run at either a sub daily or daily time step.

### 2.2.1. Modelling approach and structure

The conceptual framework for SWAT consists of a two stage modelling approach; the first is constituent generation (runoff, sediments, nutrients, pesticides) and the second is transportation (or routing) of the constituents through a stream network.

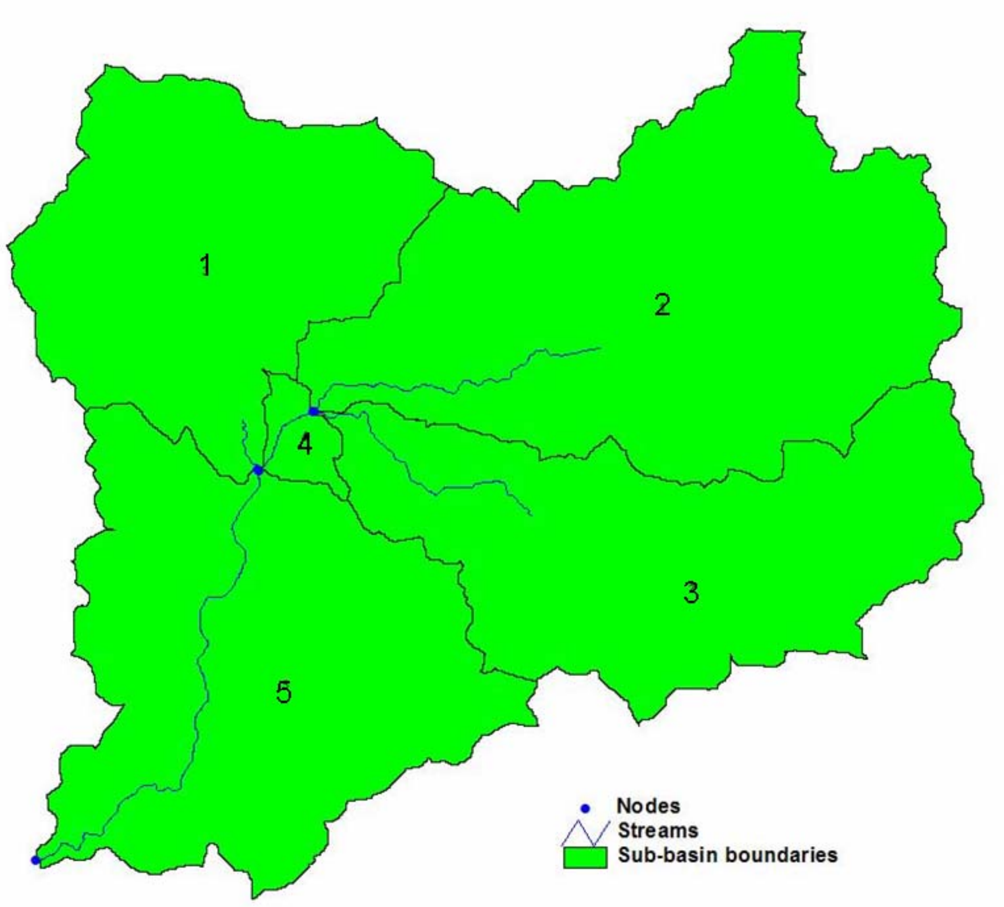
The SWAT2000 (Neitsch *et al.*, 2001) GIS interface is used to partition a catchment into a number of sub-catchments using an inputted digital elevation model (DEM). This is an automated process with a model user defining the minimum area threshold for sub-catchment delineation (Neitsch *et al.*, 2001). Sub-catchments are linked by a network of nodes and channels to represent a stream network for a catchment area. Within each sub-catchment there can be one or many hydrologic response units (HRUs), which represent a unique combination of land use and soil type.

HRUs are derived from a GIS overlay of land uses and soils (Neitsch *et al.*, 2001). The user may chose to have every HRU combination that occurs represented in the model, or may chose to set a minimum area threshold to limit the number HRUs to be modelled. Computational efficiencies are gained by selecting a threshold to minimise the number of HRUs. All matching HRU combinations within a single sub-catchment are considered as a lumped area in the model.

Runoff and other constituents are generated at HRU scale. The type of model used at the HRU scale is similar to GLEAMS and PERFECT in its approach to soil and land use representation and has been labelled “bio-physical” (Littleboy, 1992a). Agricultural practices such as tillage type, and fertiliser and herbicide application rates and methods, can be explicitly described and simulated for each HRU.

SWAT can be described as a semi-distributed model, with each sub-catchment distributed spatially and matching HRU lumped within a sub-catchment. Unlike a fully distributed model no interactions and no fluxes occur across boundaries of HRUs within the model (Chen and Mackay, 2004). Instead, streamflow and pollutant loads generated at HRU scale within a sub-catchment are summed on an area weighted basis and used as input to the sub-catchment channel reach. SWAT then models constituent routing (including losses and transformations) through channel sections to the catchment outlet. Figure 1 shows a sub-catchment delineation for the Hodgson Creek catchment. It has 5 sub-catchments and three nodes which link sub-catchment channel networks to the catchment outlet.

**Figure 1 : Sub-catchment delineation of the Hodgson Creek Catchment as used in this study**




### 2.2.2. Model processes important to this study

**Hydrologic Processes**

"No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed." (Neitsch *et al.*, 2001).

The hydrologic cycle, as it applies to water held in a soil, simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad \textbf{2.1}$$

Where;

$SW_t$ is the final soil water content (mm $H_2O$),

$SW_0$ is the initial soil water content on day $i$ (mm $H_2O$),

$t$ is the time (days),

$R_{day}$ is the amount of precipitation on day $i$ (mm $H_2O$),

$Q_{surf}$ is the amount of surface runoff on day $i$ (mm $H_2O$),

$E_a$ is the amount of evapotranspiration on day $i$ (mm $H_2O$),

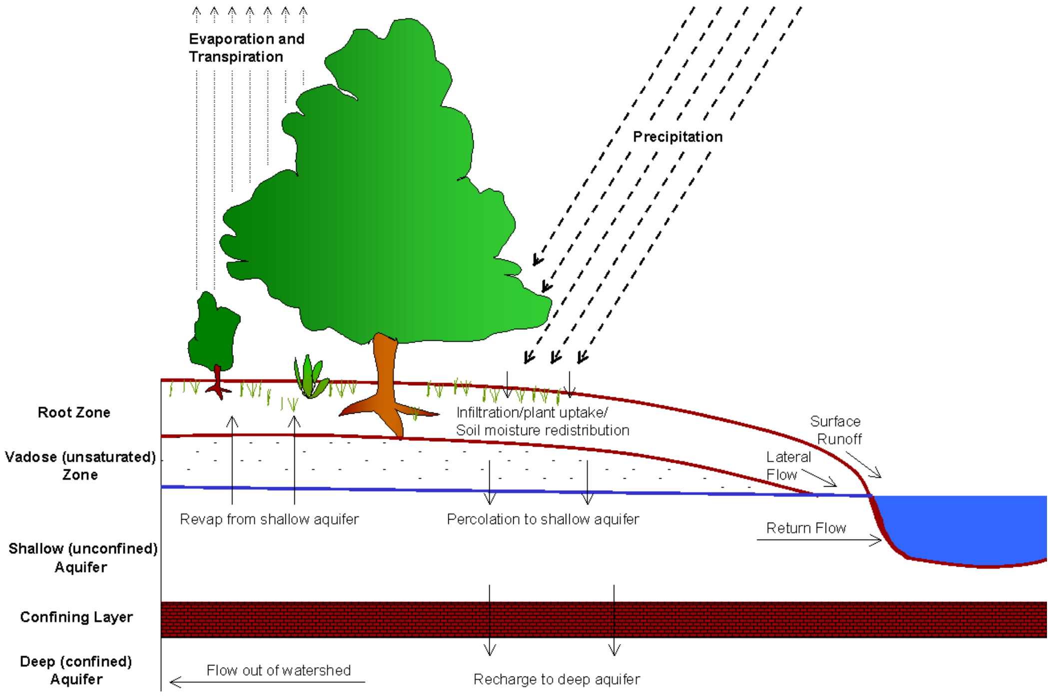
$w_{seep}$ is the amount of water entering the vadose zone from the soil profile on day $i$ (mm $H_2O$), and

$Q_{gw}$ is the amount of return flow on day $i$ (mm $H_2O$).

Soil water is updated on a daily basis by any rainfall exceeding daily runoff volume. Infiltration is partitioned into a soil profile from the surface, filling subsequent layers to total porosity. When a soil profile layer is above its defined field capacity, soil water redistribution occurs. Downward movement of water can be limited by the saturated hydraulic conductivity of individual soil layers. Redistribution from the lowest profile layer is assumed lost to the system as deep drainage. Water can be lost from the soil profile as transpiration and soil evaporation.

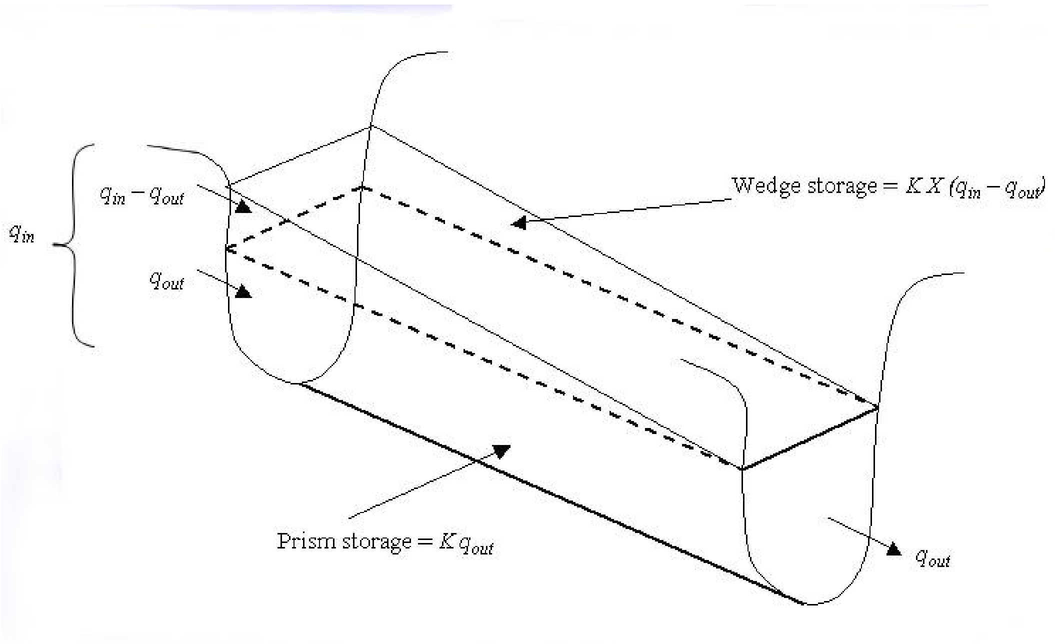
SWAT models rainfall-runoff partitioning processes using the Soil Conservation Service curve number method (SCS, 1972). Rainfall may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface can infiltrate into the soil profile or flow off as runoff. Infiltrated water is held in the soil profile until it is evaporated or transpired. Water in excess of the soils water holding capacity drains through to recharge aquifer systems or flows laterally to intersect the surface again and contributes to runoff. The potential pathways of water movement simulated by SWAT in a HRU are illustrated in Figure 2.

**Figure 2: Schematic representation of a HRU hydrologic cycle (Source: Neitsch *et al.*, 2001)**




Surface runoff is routed through the channel system using the Muskingum routing method. The Muskingum routing method represents the storage volume in a channel reach as a conceptual combination of wedge and prism storages (Figure 3). When a flood wave moves through a reach segment, inflow initially exceeds outflow and a wedge of storage is produced. As the flood wave recedes outflow exceeds inflow and a negative wedge is produced. In addition to wedge storage, a reach segment contains a prism of storage formed by a volume of constant cross-section along a reach length.

**Figure 3: Prism and wedge storages in a reach segment (Source: Neitsch *et al.*, 2001)**




For a constant velocity, the cross-sectional area of flow is assumed to be directly proportional to the discharge for a given reach segment. On this basis, the volume of the prism storage can be expressed as a function of discharge, $K \cdot q_{out}$ where $K$ is the ratio of storage to discharge and has dimension of time. In a similar manner, the volume of wedge storage can be expressed as $K \cdot X \cdot (q_{in} - q_{out})$, where $X$ is a weighting factor that controls the relative importance of inflow and outflow in determining storage in a reach. Summing these terms gives the Muskingum equation for total storage in a stream reach.

$$V_{stored} = K \cdot q_{out} + K \cdot X \cdot (q_{in} - q_{out}) \quad \textbf{(2.2)}$$

Where;

$V_{stored}$ is the storage volume ($m^3$ $H_2O$),

$q_{in}$ is the inflow rate ($m^3/s$),

$q_{out}$ is the discharge rate ($m^3/s$),

$K$ is the storage time constant for a reach, and

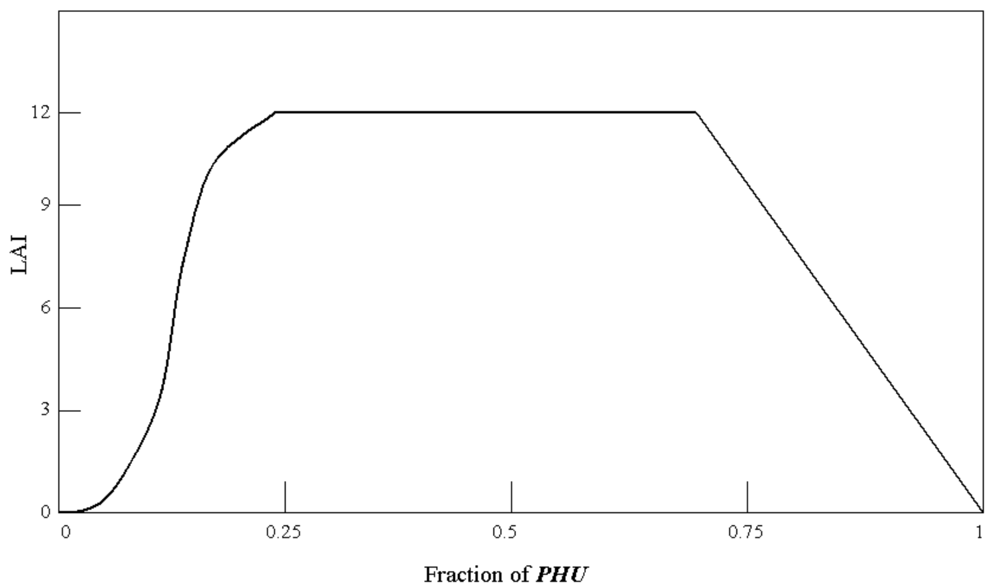
*X* is the weighting factor.

For natural rivers, *X* will fall between 0.0 and 0.3 with a mean value near 0.2 (Neitsch *et al.*, 2001).

**Plant Growth**

SWAT uses a plant growth model based on heat unit (HU) and leaf area index (LAI) method of Watson (1947). A HU is defined as each 1 degree above a specified minimum value for a particular crop accumulated on a daily basis, and plant heat units (PHU) are the total accumulated heat units required for a plant to reach maturity. Leaf area development follows an optimal curve under non-limiting conditions; an example of which is given in Figure 4, and LAI achieved is controlled by accumulation of HU's. Root length development, important to characterise plant access to soil water supply, is similarly controlled by HU accumulation. SWAT also models nutrient cycling and plant development can be limited by availability of either nitrogen or phosphorus. Once the maximum leaf area and root depth are attained they remain constant until plant death.

**Figure 4: Example of optimal plant leaf area index curve development as a function of plant heat units for a plant to reach maturity (Source: Neitsch *et al.*, 2001).**



Potential evapo-transpiration (PET) of a plant can be calculated in SWAT using the Hargreaves (1985) method. The Hargreaves method is given in Equation 2.3.

$$\lambda E_o = 0.0023 \cdot H_0 \cdot (T_{mx} - T_{mn})^{0.5} \cdot (\overline{T}_{av} + 17.8) \quad \textbf{(2.3)}$$

Where;

$\lambda$ is the latent heat of vaporization (MJ $kg^{-1}$),

$E_o$ is the potential evapotranspiration (mm $d^{-1}$),

$H_0$ is the extraterrestrial radiation (MJ $m^{-2}$ $d^{-1}$),

$T_{mx}$ is the maximum air temperature for a given day (°C),

$T_{mn}$ is the minimum air temperature for a given day (°C), and

$\overline{T}_{av}$ is the mean air temperature for a given day (°C)

While SWAT provides other options to calculate PET, the Hargreaves (1985) method was chosen for use in this project because the necessary data were readily available. This method requires daily maximum and minimum temperature and radiation values as a minimum data set. Other options to calculate PET in SWAT require data such as relative humidity and wind speed, which were not available for the study area.

Actual evapo-transpiration, which includes both transpiration and evaporation, is calculated on a daily basis as a function of PET. It incorporates extent to which leaf area has developed which controls transpiration ($E_t$) and the level of soil covered by crop residues and leaf area which controls soil evaporation ($E_s$).

$$E_t = E_0 \cdot LAI/3.0 \qquad 0 \le LAI \le 3.0 \quad \textbf{(2.4)}$$

$$E_t = E_0 \qquad LAI > 3.0 \quad \textbf{(2.5)}$$

$$E_s = E_0 \cdot cov_{sol} \quad \textbf{(2.6)}$$

Where;

$E_o$ is the PET (mm $d^{-1}$) (from Eq. 2.3)

LAI is the leaf area index

$cov_{sol}$ is the soil cover index

Crop biomass is modelled as a function of leaf area development and light interception. Intercepted sunlight is converted into biomass using radiation use efficiency for each plant species. Default values are provided in SWAT but can be defined by a model user. The maximum increase in biomass on a given day is estimated from intercepted photosynthetically active radiation (Monteith, 1977):

$$\Delta bio = RUE \cdot H_{phosyn} \qquad \textbf{(2.7)}$$

Where;

$\Delta bio$ is the potential increase in total plant biomass on a given day (kg/ha),

$RUE$ is the radiation-use efficiency of the plant (kg/ha·(MJ/m$^2$)$^{-1}$ or $10^{-1}$ g/MJ), and

$H_{phosyn}$ is the amount of intercepted photosynthetically active radiation on a given day (MJ $m^{-2}$).

The amount of daily solar radiation intercepted by leaf area of the plant is calculated from Beer's law:

$$H_{phosyn} = 0.5 \cdot H_{day} \cdot \left(1 - \exp\left(k_{\ell} \cdot LAI\right)\right) \qquad \textbf{(2.8)}$$

Where;

$H_{day}$ is the incident total solar (MJ $m^{-2}$),

$k_{\ell}$ is the light extinction coefficient, and

$LAI$ is the leaf area index.

Upon maturity of annual crops a percentage of biomass is removed as crop yield and the remainder converted to stubble residue. Stubble residue mass is reduced at a constant percentage per day to simulate decay.

**Erosion and Sediment Transport**

Sediment yield is estimated for each HRU by the Modified Universal Soil Loss Equation (MUSLE) as described by Williams (1995) as:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad \textbf{(2.9)}$$

Where;

sed is the sediment yield on a given day (metric tons),

$Q_{surf}$ is the surface runoff volume (mm/ha),

$q_{peak}$ is the peak runoff rate (m3 $s^{-1}$),

$area_{hru}$ is the area of the HRU (ha),

$K_{USLE}$ is the USLE soil erodibility factor (0.013 metric ton $m^2$ hr/($m^3$-metric ton cm)),

$C_{USLE}$ is the USLE cover and management factor,

$P_{USLE}$ is the USLE support practice factor,

$LS_{USLE}$ is the USLE topographic factor, and

CFRG is the coarse fragment factor.

The Universal Soil Loss Equation (USLE) uses rainfall as an indicator of erosive energy to estimate long term average erosion whereas MUSLE uses daily runoff amount and peak runoff rate to simulate daily erosion and sediment yield. The peak runoff rate is an indicator of the erosive power of a storm and so can be used to predict sediment loss (Neitsch *et al.*, 2001).

Calculation of runoff volume has been described earlier and SWAT calculates the peak runoff rate with a modified rational method. The peak runoff rate is the maximum runoff flow rate that occurs with a given rainfall event.

The amount of sediment that is transported from a reach segment per day is calculated by multiplying streamflow and sediment concentration, where the sediment concentration is calculated as:

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{spexp} \quad \textbf{(2.10)}$$

Where;

$conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton $m^3$ or kg $L^{-1}$),

$c_{sp}$ is a coefficient defined by the user,

$v_{ch,pk}$ is the peak channel velocity (m $s^{-1}$), and

spexp is an exponent defined by the user. The exponent, spexp, normally takes a value of 1.5 (Neitsch *et al.*, 2001).

The peak channel velocity, $v_{ch,pk}$, is calculated from the discharge equation:

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \quad \textbf{(2.11)}$$

Where;

$q_{ch,pk}$ is the peak flow rate ($m^3$ $s^{-1}$), and

$A_{ch}$ is the cross-sectional area of flow in the channel ($m^2$). The peak flow rate is defined as:

$$q_{ch,pk} = prf \cdot q_{ch} \quad \textbf{(2.12)}$$

Where;

*prf* is the peak rate adjustment factor, and

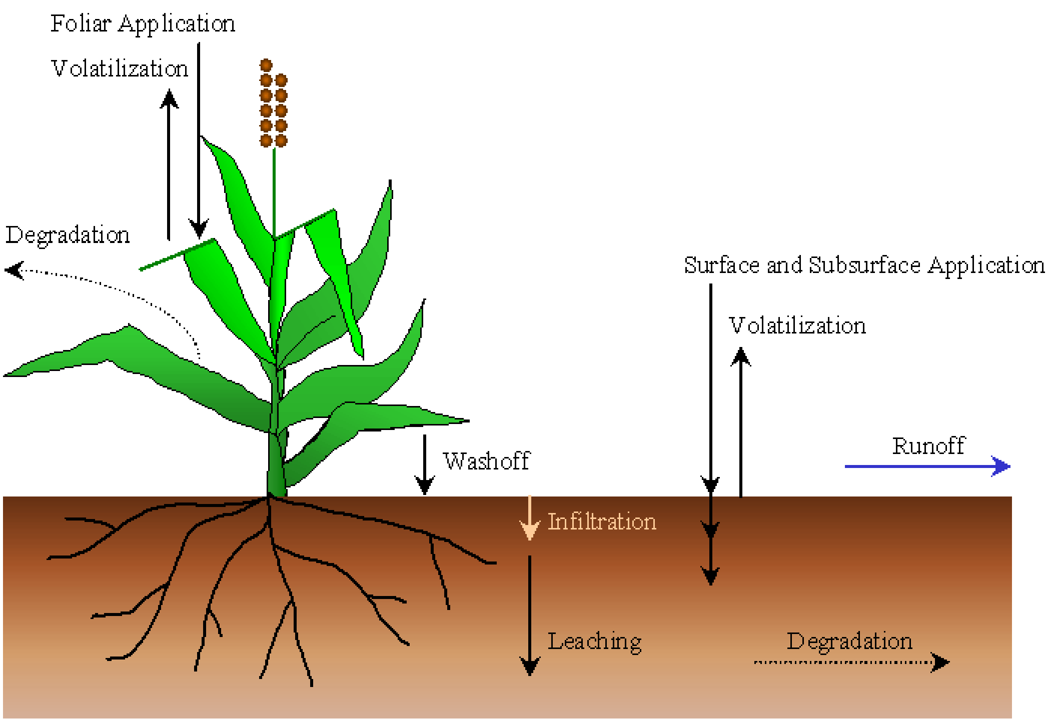
$q_{ch}$ is the average rate of flow ($m^3 s^{-1}$).

**Herbicide Processes**

There are three distinct processes affecting herbicide loads exported from a catchment; they are dissipation, mobilisation and transportation (Neitsch *et al.*, 2001). Dissipation and mobilisation are paddock processes and are simulated in SWAT in a similar way to the GLEAMS model (Leonard *et al.*, 1987). Transport through a channel network uses a mass balance approach developed by Chapra (1997) for in-channel transport and transformation processes.

Mobilisation of an herbicide can occur either as a soluble phase or by adsorption to sediment. The degree to which either process dominates is determined by a herbicides soil adsorption coefficient, normalised for soil organic carbon content (Neitsch *et al.*, 2001). Figure 5 shows potential herbicide pathways and processes simulated in SWAT.

**Figure 5: Herbicide fate and transport in SWAT (Source: Neitsch *et al.*, 2001)**




The herbicide concentration in a soil surface determines the amount that is available for extraction into surface runoff or movement into a soil profile (Leonard *et al.*, 1987). SWAT estimates this soil concentration on a daily basis by using a first order dissipation kinetics approach. The dissipation rate is controlled by an herbicides half life, defined as the number of days required for herbicide soil concentration to be reduced by one-half.

Equation 2.13 is used to quantify herbicide degradation or removal in all soil layers as governed by first-order kinetics:

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp\left[-k_{p,soil} \cdot t\right] \tag{2.13}$$

Where;

$pst_{s,ly,t}$ is the amount of herbicide in a soil layer at time $t$ (kg pst $ha^{-1}$),

$pst_{s,ly,o}$ is the initial amount of herbicide in a soil layer (kg pst $ha^{-1}$),

$k_{p,soil}$ is the rate constant for degradation or removal of the herbicide in soil ($day^{-1}$), and

$t$ is the time elapsed since the initial herbicide amount was determined (days).

The rate constant is related to half-life as follows:

$$t_{1/2,s} = \frac{0.693}{k_{p,soil}} \quad \textbf{(2.14)}$$

Where;

$t_{1/2,s}$ is the half-life of a herbicide in the soil (days).

Adsorption coefficient ($K_d$) is the primary factor controlling herbicide water/sediment partitioning and is used to describe partitioning of herbicide movement between soluble and adsorbed phases in runoff. It is defined by Leonard and Wauchope in Knisel (1980) as;

$$K_d = C_s / C_w \quad \textbf{(2.15)}$$

Where;

$C_s$ is the herbicide concentration in soil or solid phase (mg $kg^{-1}$), and

$C_w$ is the herbicide concentration in solution phase (mg $L^{-1}$)

While the adsorption coefficient is a constant for a particular chemical, to characterise the behave observed across various soils it is normalised for organic carbon ($K_{oc}$) where;

$$K_{oc} = K_d \cdot 100/ OC \quad \textbf{(2.16)}$$

Where;

OC is the organic carbon content of a soil expresses as a percentage of soil mass.

OC is not considered to vary widely in black cracking clays, the dominant soil cropped in the study are, and is typically 0.8-1.2% (Harris *et al.*, 1999).

The concentration of herbicide in runoff calculated by SWAT allows for the initial vertical movement of chemical associated with infiltration. The change in the amount of herbicide contained in the surface soil layer due to transport in solution with percolation flow is a function of time, concentration and amount of flow:

$$\frac{dpst_{s,ly}}{dt} = 0.01 \cdot C_{solution} \cdot w_{mobile} \qquad \textbf{(2.17)}$$

Where;

$pst_{s,ly}$ is the amount of herbicide in a soil layer (kg pst $ha^{-1}$),

$C_{solution}$ is the herbicide concentration in solution (mg $L^{-1}$ or g $ton^{-1}$), and

$w_{mobile}$ is the amount of mobile water on a given day (mm $H_2O$).

Herbicide attached to soil particles may be transported by surface runoff. This phase of herbicide transport is associated with sediment loading from a HRU. Accordingly changes in sediment loading will be reflected in the loading of adsorbed herbicide. The amount of herbicide transported with sediment is calculated using a loading function developed by McElroy *et al*. (1976) and modified by Williams and Hann (1978).

$$pst_{sed} = 0.001 \cdot C_{solidphase} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{pst:sed} \qquad \textbf{(2.18)}$$

Where;

$pst_{sed}$ is the amount of adsorbed herbicide transported to the main channel in surface runoff (kg pst $ha^{-1}$),

$C_{solidphase}$ is the concentration of herbicide on sediment in the top 10 mm (g pst metric ton $soil^{-1}$),

$sed$ is the sediment yield on a given day (metric tons),

$area_{hru}$ is the HRU area (ha), and

$\varepsilon_{pst:sed}$ is the herbicide enrichment ratio.

Once a herbicide has been mobilised it is then routed through the stream network. Within each reach there are two major herbicide pools with ten herbicide processes being calculated (Neitsch *et al.*, 2001). The herbicide mass balance equation as described by Chapra (1997) for the reach segments are given in Equation 2.19 with all units in mg of herbicide.

$$\Delta pst_{rchwtr} = pst_{in} - (pst_{sol,o} + pst_{sorb,o}) - pst_{deg,wtr} - pst_{vol,wtr} - pst_{dtl,wtr} + pst_{rsp,wtr} \pm pst_{dif} \quad \textbf{(2.19)}$$

Where;

$\Delta pst_{rchwtr}$ is the change in herbicide mass in the water layer,

$pst_{in}$ is the herbicide added to a reach via inflow,

$pst_{sol,o}$ is the dissolved herbicide removed from a reach via outflow,

$pst_{sorb,o}$ is the adsorbed herbicide removed from a reach via outflow,

$pst_{deg,wtr}$ is the amount of herbicide removed from water via degradation,

$pst_{vol,wtr}$ is the amount of herbicide removed from water via volatilisation,

$pst_{stl,wtr}$ is the amount of herbicide removed from water via settling,

$pst_{rsp,wtr}$ is the amount of herbicide added to water via re-suspension, and

$pst_{dif}$ is the amount of herbicide transferred between water and sediment by diffusion, and;

$$\Delta pst_{rchsed} = - pst_{deg,sed} + pst_{stl,wtr} - pst_{rsp,wtr} - pst_{bur} \pm pst_{dif} \quad \textbf{(2.20)}$$

Where;

$\Delta pst_{rchsed}$ is the change in herbicide mass in the sediment layer,

$pst_{deg,sed}$ is the amount of herbicide removed from sediment via degradation,

$pst_{stl,wtr}$ is the amount of added to sediment via settling,

$pst_{rsp,wtr}$ is the amount of herbicide removed from sediment via re-suspension,

$pst_{bur}$ is the amount of herbicide removed from sediment via burial, and

$pst_{dif}$ is the amount of herbicide transferred between water and sediment by diffusion.

While there are many processes modelled in this set of equations, importantly a number of them keep a herbicide in the expected ratio between sediment and liquid phases during transport. Partitioning between the solid and liquid phases in the sediment pool is calculated based on the herbicide sorption coefficient ($K_d$).

## 2.3. APPLICATIONS OF THE SOIL AND WATER ASSESSMENT TOOL

The published literature includes many papers where SWAT has been tested against observed data from around the world (e.g. Santhi *et al.*, 2001; Grizzetti *et al.*, 2003; Tripathi *et al.*, 2003; Watson *et al.*, 2003). This testing has covered a large range of scales and landscapes. Most papers show an ability to adequately predict streamflow on a monthly basis. Varying success is reported for constituent transport and few studies have tested the herbicide model of SWAT against measured data.

In reviewing the literature on the application of SWAT it became clear that considerably more work has been done in the United States of America (USA) than elsewhere. The authorship of publications shows that the SWAT model development team has been very active in applying their model to many areas across the USA. Many of the papers feature authors directly involved in SWAT model development through the USDA in Temple, Texas. The USA papers are presented separately to studies from other countries because it was assumed that these authors have a greater ability to maximise the models performance.

### 2.3.1. Application of SWAT in the United States of America

The largest scale of application of SWAT was also one of the earliest. Srinivasan *et al.* (1997) found that they were able to apply SWAT to a 600,000 $km^2$ catchment extending from lower Texas into Mexico. Their work demonstrated the ability to apply SWAT over large areas by using the GIS interface to build a model sub-catchment framework. Unfortunately results showed a poor fit for hydrology and did not achieve a stated aim of modelling water quality. The authors attributed hydrologic errors to be due to a lack of knowledge on water extraction from a number of large storages which were unaccounted for in the model. Sediment yield was predicted, but no observed data were presented for comparison. This paper demonstrated an early ability to effectively use GIS software to build a hydrologic model framework but did not establish the credentials of SWAT as a useful water quality model.

Two studies (Santhi *et al.*, 2001; Neitsch *et al.*, 2002), both by the SWAT development team, set out to demonstrate the ability of SWAT to be useful for testing Total Maximum Daily Load (TMDL) targets under the US Clean Water Act. They used small catchments in Texas to demonstrate SWAT capabilities.

Santhi *et al.* (2001) tested SWAT on a 477 $km^2$ catchment and found that they were able to predict monthly streamflow (mm) with coefficient of determination ($R^2$) > 0.9. Monthly sediment yield (t/ha) and nutrient yield (kg/ha) were predicted with $R^2 > 0.9$. They concluded that SWAT was able to successful represent hydrology and water quality processes for the catchment, with the exception of some under prediction of nitrogen.

Neitsch *et al.* (2002) then applied SWAT to a 242 $km^2$ catchment to test the models ability to predict atrazine and metolachlor processes. The study showed that with no calibration, they were able to predict daily herbicide concentrations within an order of magnitude. There was no attempt to improve the predictions through calibration to improve model results. This study was presented a demonstration of the capacity of a physical based model to describe catchment processes using measured input data alone. This study demonstrated potential for SWAT as a tool to describe catchment scale herbicide generation and transportation.

SWAT was then applied to studies aimed at improving water quality in catchments providing a water supply to New York State. Cerucci and Conrad (2003) were able to adequately represent the surface hydrology on a monthly basis for a 37 $km^2$ catchment, however the sediment and phosphorus calibration showed poor results with loads frequently over predicted. Gitua *et al.* (2004) used SWAT to derive initial predictions of catchment loading for dissolved phosphorus. These loadings were established without catchment data to calibrate against and so the model results are unproven. A phosphorus reduction due to best practice adoption was modelling using an reduction efficiency. Neither paper showed SWAT performing as well as it had in the earlier Texas studies.

### 2.3.2. Application of SWAT worldwide

**SWAT applications in Europe**

A version of SWAT, called SWAT-G (Germany), was applied by Eckhardt (2001) to a German catchment characterised by shallow soils over hard rock. The catchment observations showed significant interflow which were modelled by revising the calculation of percolation and interflow. These model changes resulted in a good fits with observed streamflow, however water quality simulations were not undertaken.

SWAT was applied in Finland to a 1680 $km^2$ by Grizzetti *et al.* (2003) with good predictions of flow, nitrogen and phosphorus loads. The key purpose of the paper was to determine retention rates of nutrients within the catchment. They found some under estimation of peak flows and corresponding underestimation of nitrogen, however sediment and phosphorus were over predicted. Sediment over estimation was accounted for by the presence of small storages which act as sediment detention storages and were not included in the model.

In France, Conan *et al.* (2003) found that SWAT coupled with MODLOW could reasonably predict monthly streamflow and nitrogen loads for a 12 $km^2$ catchment.

In India, Tripathi *et al.* (2003) applied SWAT to a 92 $km^2$ sub-catchment with good predictions of daily hydrology, sediment and nutrient transport. They concluded that SWAT was a suitable tool for identifying sub-catchment areas for prioritisation of management actions.

**SWAT applications in Australia**

SWAT has been applied by a small number of groups within Australia, and the author has been in discussion with these groups and is familiar with the problems that were faced in their studies.

SWAT was applied by Dougall *et al.* (2003) to predict the impact of agricultural management on sediment load for a 300 $km^2$ catchment in Central Queensland. The model over predicted both total runoff and sediment load but gave a good representation of the sediment concentration in runoff.

Watson *et al.* (2003) applied SWAT to an 1157 $km^2$ catchment in South-East Victoria. They were able to calibrate the model on monthly streamflow with $R^2$ and Nash-Sutcliffe coefficients greater than 0.75. However it was shown by the authors that groundwater and tree growth components of SWAT did not perform adequately with their catchment. They found that the groundwater model used in SWAT was over-simplified to a point where it could not be applied to the system they were studying, resulting in poor representation of the baseflow component of streamflow. They also found that the tree growth model treated trees similarly to annual crops resulting in unrealistic annual fluctuations in biomass. Further, while leaf drop may occur in dry sclerophyll forests, it is more commonly associated with drought rather than day length as is assumed in SWAT. Watson *et* *al.* (2003) concluded that the shortcomings they identified were sufficient to affect SWAT's ability to accurately model the water balance of catchments in Australia.

Sun and Cornish (2005) used SWAT on a 437 $km^2$ Northern New South Wales catchment to predict shallow groundwater recharge. Their conclusions were that recharge occurs only in wet years and it is dominated by a few significant periods. This finding suggests that bore responses are much more a function of climatic conditions than land use. Sun and Cornish suggest that SWAT provides an alternative approach to previous point scale modelling of recharge for their region, but there is a need for improvement to the bypass flow component of SWAT so that it can be used to model cracking vertosol soils.

While all these Australian authors were able to reasonably represent catchment hydrology, many model processes were questioned. There has been no work to date on using SWAT for predicting herbicide fate in Australia.

### 2.3.3. An opportunity to use SWAT to study herbicide transport in Australia

The review of literature for applications of SWAT showed that there has been little testing to date of the herbicide sub-model. Most papers show an ability to adequately represent hydrology on a monthly basis, whereas the ability to predict sediment and nutrient transport varied. No papers, outside of the USA, were found to establish the ability of SWAT to predict herbicide concentrations. This review clearly demonstrates that the opportunity exists to test the ability of SWAT for herbicide transport studies in the Australian context.

## 2.4. DESCRIPTION OF THE CASE STUDY AREA (HODGSON CREEK CATCHMENT) AND GRAIN FARMING PRODUCTION SYSTEM

For the purpose of testing the applicability of SWAT for Australian conditions, the Hodgson Creek catchment on the Eastern Darling Downs in South-East Queensland, was selected for use as a case study. This catchment is representative of many catchments in the North East Australian cropping region with a mix of land uses (native forest, pastures and cropping) and topography (steep rangeland to flood plains).

The Hodgson Creek catchment has an area of about 570 $km^2$ and is heavily modified for use as farming country, with 50 % used for cropping and 45 % used for grazing. The balance includes urban, rural-residential and transport areas. Soils are predominantly heavy black cracking clays (vertosols) derived from basalt. There is a strong rainfall gradient across the catchment with average annual rainfall around 950 mm/year in the North-East upland falling to around 650 mm/year at the South-West floodplain outlet.

Considerable data sets have been collected for both paddock and catchment scale water quality parameters, including erosion, suspended sediment, nutrients and herbicides (Freebairn and Wockner, 1986; Rattray *et al.*, 2002; Rattray *et al.*, 2007).

### 2.4.1. Characteristics of Hodgson Creek catchment

**Geology and Soils**

The geology of the Hodgson Creek catchment consists of Marburg sandstones from the Jurassic period overlain by basalt from volcanic eruptions in the Tertiary period (Harris *et al.*, 1999). The dominant soils are basaltic derived deep to very deep self-mulching black cracking clays (vertosols) of basaltic colluvium and alluvium, with very shallow clays and loams on rises (Harris *et al.*, 1999). A map of soils of the area sourced from the Queensland Department of Natural Resources and Mines (NR&M) is given in Appendix A, Map 3, and a full description of the soil parameters values derived for the SWAT model given in Section 3.1.1. The black cracking clays are highly fertile and have considerable water storage capacity. Alluvial soils in the lower floodplain have plant available water capacities of up to 300 mm to 1.5 m.

**Land Use and Management**

Land use for this study was classified by interpretation of aerial photography in conjunction with field investigations. A map of land use for Hodgson Creek catchment is given in Appendix A, Map 5.

The major land use for the catchment is dry land cropping of cereal grains, which account for 51 % of total area. A further 45% of the area is used for grazing equally split between cleared and un-cleared country. The remaining 4% of land use is urban, rural-residential and transport areas.

Land management practices, particularly cultivation are important for modelling of this landscape because of cultivation effects on erosion. Conservation tillage practices can reduce average annual erosion by an order of magnitude when compared to conventional or traditional cultivation practices (Freebairn and Wockner, 1986; Rattray *et al.*, 2005).

Land management was derived by interviews with selected local landholders and local agronomists familiar with farming practices in the area. A sub-catchment of the Hodgson Creek in the South-West, called Felton Valley, was chosen to derive these estimates, with the data then extrapolated to the whole catchment. This provided a means of estimating the relative adoption of tillage practices and herbicide use patterns for the catchment. This work suggested adoption of conservation tillage practice accounts applied to less than 30% of the cultivated area, with zero tillage practices around 10-15% of the area and 15-20% minimum tillage. This work also suggested that atrazine is used on about 60% of the summer crop area planted in the catchment (Reardon-Smith pers. comm., 2004).

Both summer and winter cereal grains are grown within the cropping system used in Hodgson Creek. Data from the National Cereal Database developed by Guthridge (2004) was used to estimate a ratio of winter crop to summer crop planting (hectares) for the catchment. Data is presented on a shire basis, with Hodgson Creek catchment straddling the four Shires; Pittsworth, Jondaryan, Cambooya and Clifton (see Appendix A, MAP 3). Cambooya shire encompasses about 60% of the Hodgson Creek catchment and the remaining part of the Cambooya shire exhibits upland areas of a similar landform to the study area. On this basis it was taken to best represent trends in crop planting and yields in this catchment.

In Figure 6 the area of winter and summer crops planted in the Cambooya are presented for the period 1977-2000 and in Figure 7 crop yields are presented. Although the record is not complete with missing data for some periods, some trends on the figures include a decrease in the area of winter crops being planted and an increase in summer crop area. Overall, total planted area for Cambooya Shire decreases by around 30% over this 20 year period. In the period from 1977 to 2000 the yield of winter crops is constant at about 1.8 t/ha (SD of 0.5t/ha), however summer crop yields increased with an average of 2.7 t/ha (SD of 0.9 t/ha).

**Figure 6 : Cambooya Shire crop planted areas for winter and summer cereal crops (Source: Gutheridge, 2004).**

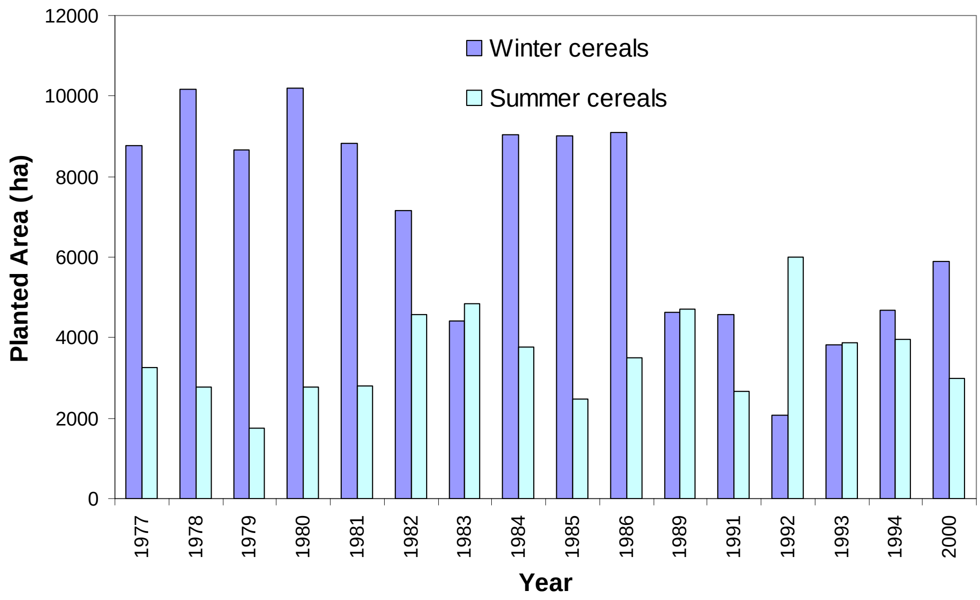
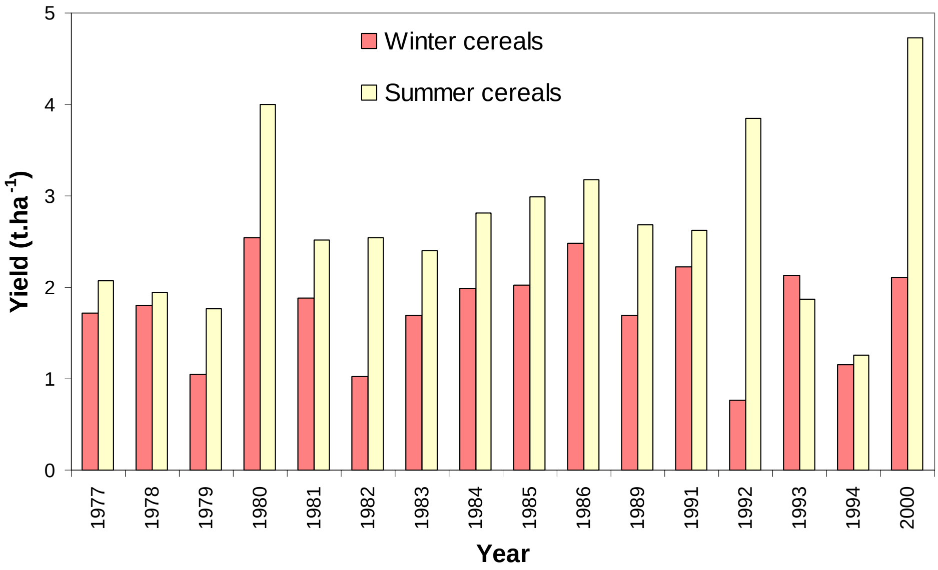


**Figure 7: Cambooya Shire crop yields for winter and summer cereal crops (Source: Gutheridge, 2004).**




**Climate**

Hodgson Creek catchment has a sub-tropical climate (Harris *et al.*, 1999). Rainfall is summer dominant and highly variable. There is a strong rainfall gradient across the catchment with average annual rainfall around 950 mm/year in the North-East upland falling to around 650 mm/year in the South-West floodplain outlet, a gradient of greater than 10 mm/year per kilometre. Widespread rainfall for the area is typically low intensity and can either be associated with upper level troughs or rain depressions. However summer storms are frequently high intensity storm cells producing more than 100 mm/hr rainfall with a high potential for erosion, especially where soils are bare.

Air temperatures for the area also vary, with the Western catchment being up to 3 degrees warmer than the more elevated Eastern escarpment. Summer temperatures for the December-January months average 15-30 $^{o}$C with winter temperatures in May-June 5-20 $^{o}$C. Periods of frost during winter and heatwaves (>38 $^{o}$C for three consecutive days) during summer can also occur (Harris *et al.*, 1999).

### 2.4.2. Grain farming production system

Grain farming in the Northern grains region of Australia (an area from Dubbo to Emerald) produces mainly wheat, sorghum, maize and barley. Farming systems have changed radically in the last century on the Darling Downs. Conventional farming practices in the early part of the century comprised wheat monoculture systems where the wheat stubble was burnt after harvest for disease control. Grain sorghum is now a major summer grain crop in most regions in Queensland and it plays a key role in providing feed grains to the beef, dairy, pig and poultry industries (Clarke and Wylie, 1997). Sorghum popularity can be attributed to factors of improved agronomy and familiarity with sorghum leading to improved yields. Atrazine and/or metolachlor are a primary form of weed control in sorghum in these farming systems.

**Tillage practices**

With the advent of machinery capable of planting directly into paddocks with stubble and the introduction of herbicides, minimum and zero tillage farming systems are now more common. Adoption of these techniques in the Darling Downs has been highest on the extensive floodplains and in the Western farming areas, while upland areas have lagged behind. Estimates by the author put the adoption of conservation tillage at around 30 % for the Hodgson Creek catchment. Minimum tillage is more prevalent than zero tillage in these conservation tillage practices but the mix is subject to seasonal conditions and weed pressure. There remains significant scope for increased adoption of conservation tillage in upland areas. Improved tillage practice represents a major pathway towards improved water quality from upland catchments such as Hodgson Creek (Rattray *et al.*, 2005).

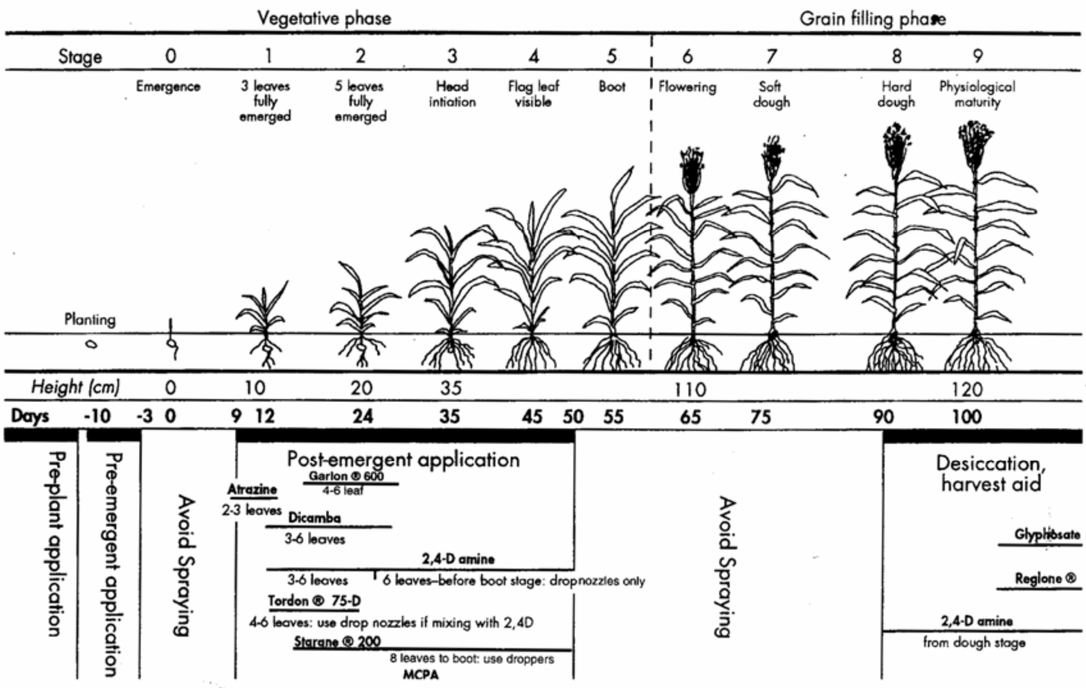
The effects of different cultivation management practices on runoff and erosion have been well characterised for the study area (Freebairn and Wockner, 1996). A long term study site just outside the village of Greenmount (in the South-East of the Hodgson Creek catchment) was operated over a 16 years period to 1991. A set of 5 contour bays, each about 1 hectare in size, were monitored with measurements and observations taken of crop yield, stubble cover on the soil surface, soil moisture to 1.5 metres, rainfall, runoff, sediment in runoff and erosion. This has been one of the most comprehensive studies of paddock scale hydrology undertaken within Australia and many of the results have become a benchmark to describe the effects of conservation tillage on erosion. This study concluded that increased cover reduces erosion significantly and increases the potential for stored soil moisture.

Conservation cropping practices such as stubble retention and minimum tillage result in improved water use efficiency and soil conservation. They currently rely on the use of herbicides for weed control. Without these herbicides, farmers would face problems in maintaining conservation tillage systems and have to place a greater reliance on tillage, increasing the risk of erosion and off site water quality impacts.

**Herbicide use**

A study of herbicide usage for the Condamine-Balonne-Culgoa catchment area by Rayment and Simpson (1993) showed that atrazine was the most used chemical in agriculture at that time. Hodgson Creek is a sub-catchment of the Condamine catchment. It was estimated that 260 tonnes of atrazine active ingredient (a.i.) were being used on an annual basis within the basin. The average rate of application was estimated at 1.8-3.3 kg/ha a.i. annually for sorghum. Usage figures for metolachlor are not available. While a number of herbicides are registered for use in sorghum (QDPI, 2002), the primary recommendation is the use of a residual herbicide, either atrazine or metolachlor, for most weed control (QDPI, 2000). The choice of rate and timing of application is based on the weed spectrum. Application of residual herbicides can be pre-plant, pre-emergent or post-emergent. Figure 8 shows the chemicals suitable at the various crop stages for sorghum (QDPI, 2000). . Local agronomic knowledge (Reardon-Smith pers. comm., 2004) suggests that for Hodgson Creek atrazine is used mostly as a post emergent herbicide at a rate of 2.0 to 3.0 l/ha (600 g/l a.i.), in a tank mix with floxypyr or 2,4-D, for broadleaf weed control. It may be used pre emergent in a mix with metolachlor or alone as a pre emergent at 2.5 to 4.5 l/ha, but this would be generally physically incorporated into the soil at planting (80 %), or incorporated by rain (20 %)  As suggested earlier, for Hodgson creek 60 % of summer crops are currently using residual herbicides.  Due to the low adoption of conservation tillage herbicide usage has the potential to significantly increase.

**Figure 8 : Sorghum crop stages and herbicide choices. (Source: QDPI, 2000)**




## 2.5. PADDOCK MANAGEMENT PRACTICES TO REDUCE HERBICIDE LOSSES OFF FARM

The premise for using a bio-physical modelling approach is that it allows explicit comparison of farm management practices; that is, it allows the individual farm management practices to be simulated to define the impact that the practice may have on residual herbicide dynamics.  Therefore, a list of the most likely practices that would need to be modelled were compiled, and these were compared with SWAT's model structure and processes modelled to check that practices could be modelled with SWAT.  A review of the Best Management Practices (BMP) for reducing residual herbicide movement off-farm was conducted to determine the key practices that would need to be modelled.

There are a number of guidelines around the world that have been developed for reducing environmental impacts of residual herbicides. This study identified two notable examples by the Kansas University (Devlin *et al.*, 2000) and the Ontario Ministry of Agriculture and Food (2003) "Best Management Practices for Agriculture" series. Table 4 shows a summary of key practices recommended in these publications and a short description of each practice in the first column. The second column notes whether it was anticipated this practice could be modelled using SWAT and the third column provides details on an anticipated modelling approach that would be taken (or reason for why the practice cannot be modelled for a negative case).

| **Best Management Practice description** | **Can it be modelled?** | **Modelling approach** |
|---|---|---|
| **1.** Incorporation of herbicide into the top 5cm of soil following application. This moves a portion of the herbicides away from the mixing zone (i.e. top 1cm of soil). | Yes | SWAT allows tillage and mixing of soils layers. After herbicide application, but before planting, add a tillage to mix soil to 5cm. |
| **2.** Using alternative herbicides where possible. This reduces the total volume of herbicide being applied at a catchment scale. | Yes | Reduce area of catchment where herbicide is applied by applying to less HRU's. |
| **3.** Banding application over a crop row. This reduces total volume of herbicide applied by only applying to a crop row, leaving an inter-row untreated. | Yes | SWAT allows the rate of herbicide (kg/ha) to be defined. Reduce the rate of application by percentage of area banded (i.e. 50%). |

| | | |
|---|---|---|
| **4.** Improving fallow weed management or alternatively maximise crop competition to reduce reliance on atrazine for weed control. | Yes | SWAT allows the rate of herbicide (kg/ha) to be defined. Modelling would involve reducing the rate of application by a prescribed amount. |
| **5.** Change timing of application to avoid high risk periods. This practice aims to avoid application during those times when runoff and erosion are highest. | Yes | SWAT allows application date to be defined. Analyse runoff and erosion data and a change of application date to periods when these are lower. |
| **6.** Use a split application of herbicide. This practice aims to spread risk and reduce peak loads of herbicide in a soil at any given time | Yes | SWAT allows multiple application date to be defined. |
| **7.** Conservation tillage. This helps to retain stubble cover and reduces runoff and erosion. | Yes | SWAT allows tillage practices to be defined. Reduce number of tillage operations during fallow periods. |
| **8.** Opportunity cropping. Increasing cropping frequency utilises soil moisture and reduces runoff. | No | SWAT can allow crop rotations to be defined, however opportunity cropping requires reactive decision making which SWAT does not accommodate. |
| **9.** Avoid applying herbicides to soils with a higher risk of runoff and erosion. This aims to remove areas of highest contribution. | Yes | Analysis of the modelled outputs should indicate those areas contributing most to the system load. These can be avoided for application. |

| | | |
|---|---|---|
| **10.** Providing water and sedimentation control areas. | Yes | SWAT allows in stream storages to be added into a stream network. |
| **11.** Grass waterways to slow movement of water, allowing sediment to be deposited. | Yes | SWAT allows filter areas to be applied at the HRU scale. These act as filters to sediments and herbicides. |
| **12.** Avoid application to wet soils when large rainfall is forecast. This is similar to No.5 but more tactical. | No | SWAT does not allow reactive decision based rules to be applied, e.g. "apply only when soil water <80 % of field capacity" cannot be used. |
| **13.** Maintaining vegetation buffers around sensitive areas. This allows a distance between an application area and stream edge. | No. | The model does not define HRU proximity to stream due the lumped nature of a HRU within sub-catchments. Therefore a buffer area cannot be modelled. |

**Table 4 : Herbicide application best management practices to reduce environmental risks**

Those practices that can be modelled can be grouped into three main areas;

- Reducing herbicide at the paddock source by, reducing inputs, or diluting concentration at soil surface, or strategically changing the timing of application (BMP 1-6 ),
- Reducing the transport mechanism by reducing runoff or erosion (BMP 7), and
- Intercepting herbicide during transport (BMP 10 -11).

Those BMP that cannot be modelled with SWAT are those that rely on tactical decision making (i.e. reactive decisions), and those that require the model to explicitly identify application locality (i.e. proximity to streams).

Unlike models such as PERFECT (Littleboy *et al.*, 1992a), SWAT does not allow tactical operations during simulations. This precludes modelling opportunity cropping, where crop planting is based on soil moisture rather than a fixed rotation. In PERFECT a check is put in the model to trigger planting when certain soil moisture conditions are met resulting in variable planting dates from year to year. SWAT does not allow this rule and uses a fixed planting date from year to year.

The other BMP that is not able to be modelled is the vegetation buffer as this requires explicit knowledge of the spatial proximity of a HRU to stream. As SWAT lumps all like HRU together within a sub-catchment this spatial proximity knowledge is not available and does not allow impact of planting proximity to stream to be explored.

# CHAPTER 3. DATA SOURCES AND MODEL CALIBRATION

## 3.1. MODEL INPUT DATA

The SWAT2000 model interface uses Arcview® 3.2 (ESRI, 1996) as the platform for inputting spatial data sets. The interface required a number of input layers and parameter sets, including a digital elevation model (DEM), a soil map and list of soil parameters, a land use map, and climate data. The DEM must be raster format, however soils and land use may be either raster or shape file format. Climate data is entered as point data and any number of climate data points can be entered to allow for spatial variation of climate across a catchment.

The DEM is used to define sub-catchment boundaries and a stream network. Land use and soil are entered simultaneously and HRU defined on the basis of intersected layers. During the process of intersecting the land use and soil data, the user can define a threshold area (% of the sub-catchment area) that any unique combination must achieve to be included as a HRU.

### 3.1.1. Spatial data

The first step in modelling the Hodgson Creek catchment was to define the spatial extent of the area to be modelled. The catchment boundary was defined as the catchment area above the Hodgson Creek Gauging Station (G.S.) (Station Number 422352A) as shown in Appendix A, Map 1. This map also shows the location of paddock scale hydrology and water quality studies described later in this chapter.

**Digital Elevation Model**

A 25 m resolution DEM was acquired from the Queensland Department of Natural Resources and Mines (NR&M) and is shown in Appendix A, MAP 2. The SWAT2000 interface has an Arcview® script that automates the process to define sub-catchment boundaries, stream network and slope factors. The Arcview® script also defines stream section dimensions (stream width, depth and bed slope) for each of stream reaches in a catchment. SWAT uses these dimensions in algorithms to route of water and sediment (see Equations 2.2 and

2.11). Ground truthing was conducted at key locations in the catchment and stream dimensions were measured and used in place of the default values. The Arcview® script also calculated an average hill slope and slope length for each sub-catchment, these are used in MUSLE (Equation 2.9) for erosion calculations. As the Arcview® script did not account for most of the catchment having been contoured to reduce slope length, to better represent contouring, slope length was set to 50m for all sub-catchments.

**Soils**

A soils map was sourced from NR&M for this study and is provided in Appendix A, MAP 3. The map shows 43 soils, which was considered too many to be able to adequately parameterise. The soils were amalgamated to a set of 7 dominant soils types by grouping soils with similar infiltration characteristics and plant available water capacity (AWC). This amalgamation was done by utilising local area knowledge borne from soil investigation experience (pers. comm. A.Biggs, NR&M, Toowoomba). The simplified soils map is provided as Appendix A, MAP 4.

Unlike many other aspect of the SWAT model where default values were available, the soils parameters for SWAT must be defined by the model user. A range of sources was used to define the soils parameters. The soils hydrological characteristics are given in Table 5 and the soil physical characteristics in Table 6. The depths defined in Table 5 were used in model parameterisation, and variables of Table 6 were interpolated accordingly.

| Source | Biggs NRM (pers.comm 2004) | Estimated | | Owens NR&M (pers. comm. 2004) | Dalgliesh and Foale (1998) | Dalgliesh and Foale (1998) | |
|---|---|---|---|---|---|---|---|
| **Soil name** | **Australian Soil Classification** | **Hydrologic Group** | **Depth(mm)** | **Saturated Conductivity (mm/hr)** | **Bulk density (g/g)** | **AWC (mm)** | **AWC (%)** |
| **Beauaraba** | Dermosol | C | 0-100 | 3.0 | 1.00 | 26 | 0.26 |
| | | | 100-300 | 1.0 | 1.09 | 40 | 0.20 |
| **Burton** | Ferrosol | A | 0-100 | 20.0 | 1.20 | 10 | 0.10 |
| | | | 100-300 | 30.0 | 1.23 | 21 | 0.11 |
| | | | 300-1000 | 30.0 | 1.32 | 52 | 0.07 |
| **Charlton** | Vertosol | D | 0-100 | 3.0 | 1.00 | 21 | 0.21 |
| | | | 100-300 | 1.0 | 1.09 | 42 | 0.21 |
| | | | 300-750 | 1.0 | 1.13 | 76.5 | 0.17 |
| **Irving** | Vertosol | D | 0-100 | 3.0 | 1.00 | 21 | 0.21 |
| | | | 100-300 | 1.0 | 1.09 | 42 | 0.21 |
| | | | 300-1500 | 0.1 | 1.16 | 200 | 0.17 |
| **Glenmore** | Vertosol | D | 0-100 | 3.0 | 1.02 | 25 | 0.25 |
| | | | 100-300 | 1.0 | 1.03 | 48 | 0.24 |
| | | | 300-1000 | 1.0 | 1.06 | 50 | 0.07 |
| **Kenmuir** | Dermosol | A | 0-100 | 20.0 | 1.00 | 21 | 0.21 |
| | | | 100-300 | 30.0 | 1.09 | 42 | 0.21 |
| **Waco** | Vertosol | D | 0-100 | 3.0 | 1.02 | 25 | 0.25 |
| | | | 100-300 | 1.0 | 1.03 | 48 | 0.24 |
| | | | 300-1500 | 0.1 | 1.06 | 218 | 0.18 |
| | | | 1500-3000 | 0.1 | 1.13 | 65 | 0.04 |

**Table 5: Soil hydrological parameters for Hodgson Creek SWAT model**

| Source | | Biggs NRM (pers.comm 2004) | Harris *et al.* (1999) | Harris *et al.* (1999) | Harris *et al.* (1999) | Harris *et al.* (1999) | Loch *et al.* (1998) |
|---|---|---|---|---|---|---|---|
| **Soil name** | **Depth(mm)** | **Rock (%)** | **Sand (%)** | **Silt (%)** | **Clay (%)** | **Organic Carbon (%)** | **USLE 'K'** |
| **Beauaraba** | 0-60 | 20 | 20 | 26 | 51 | 1.8 | 0.044 |
| | 60-160 | 20 | 21 | 28 | 50 | | |
| | 160-400 | 20 | 23 | 28 | 50 | | |
| | 400-550 | 20 | 66 | 16 | 18 | | |
| **Burton** | 0-100 | 5 | 18 | 20 | 61 | 2.0 | 0.014 |
| | 100-300 | 5 | 8 | 15 | 77 | | |
| | 300-600 | 5 | 7 | 8 | 84 | | |
| | 600-900 | 5 | 7 | 13 | 79 | | |
| **Charlton** | 0-100 | 1 | 25 | 21 | 52 | 2.9 | 0.049 |
| | 100-300 | 1 | 17 | 19 | 63 | | |
| | 300-600 | 1 | 12 | 15 | 71 | | |
| **Irving** | 0-100 | 1 | 9 | 19 | 70 | 2.1 | 0.044 |
| | 100-300 | 1 | 8 | 20 | 72 | | |
| | 300-600 | 1 | 8 | 19 | 71 | | |
| | 600-900 | 1 | 10 | 20 | 70 | | |
| | 900-1200 | 1 | 12 | 21 | 67 | | |
| **Glenmore** | 0-100 | 1 | 13 | 12 | 73 | 1.4 | 0.051 |
| | 100-300 | 1 | 14 | 9 | 76 | | |
| | 300-600 | 1 | 15 | 11 | 73 | | |
| | 500-1000 | 1 | 15 | 12 | 73 | | |
| **Kenmuir** | 0-200 | 20 | 27 | 28 | 34 | 5.2 | 0.014 |
| **Waco** | 0-100 | 1 | 13 | 12 | 73 | 1.4 | 0.051 |
| | 100-300 | 1 | 14 | 9 | 76 | | |
| | 300-600 | 1 | 15 | 11 | 73 | | |
| | 600-900 | 1 | 15 | 12 | 73 | | |
| | 900-1200 | 1 | 14 | 12 | 73 | | |
| | 1200-1500 | 1 | 15 | 12 | 73 | | |

**Table 6: Soil physical parameters for Hodgson Creek SWAT model**

### Adjustments to soils parameters

The water balance simulated by SWAT uses soil water store characteristics as described in section 2.2.2. As soil water store dynamics can be considered a primary factor in hydrology modelled by SWAT, it was imperative to define soil store reliably.

The water content of a soil can range from zero when the soil is oven dried to a maximum value corresponding to total porosity (TP) when the soil is saturated. For plant-soil interactions, two intermediate stages are recognized: field capacity (FC) and permanent wilting point (WP). FC is the water content found when a thoroughly wetted soil has drained for approximately two days. WP is the water content when plants growing in a soil wilt and do not recover if their leaves are kept in a humid atmosphere overnight.

In SWAT WP is calculated as a function of bulk density (BD) and clay content (%), FC is calculated as WP plus available water capacity (AWC) of the soil and TP is calculated as a function of bulk density. It was observed during setting up the model that soils data yielded results where field capacity FC exceeded TP, which is physically impossible. So either field measurements of bulk density and clay content were in error or the algorithms used in SWAT did not provide a satisfactory representation for soils in this study. Figure 9 shows sensitivity of the model to two main parameters BD and clay %. A 5 % reduction in clay content increased volumetric water by 0.015 mm/mm and an increase in BD of 0.1 $g/cm^3$ results in a reduction in volumetric moisture of 0.06 mm/mm. A potential problem arises when AWC is inputted that exceeds the volumetric moisture capacity between TP and WP. It was decided to adjust BD where necessary to get drainable porosity values (WP-FC) of 5 to 6 % volumetric. An example soil water profile developed is shown for Irving clay in Figure 10.

**Figure 9 : Relationship between bulk density and volumetric moisture.**

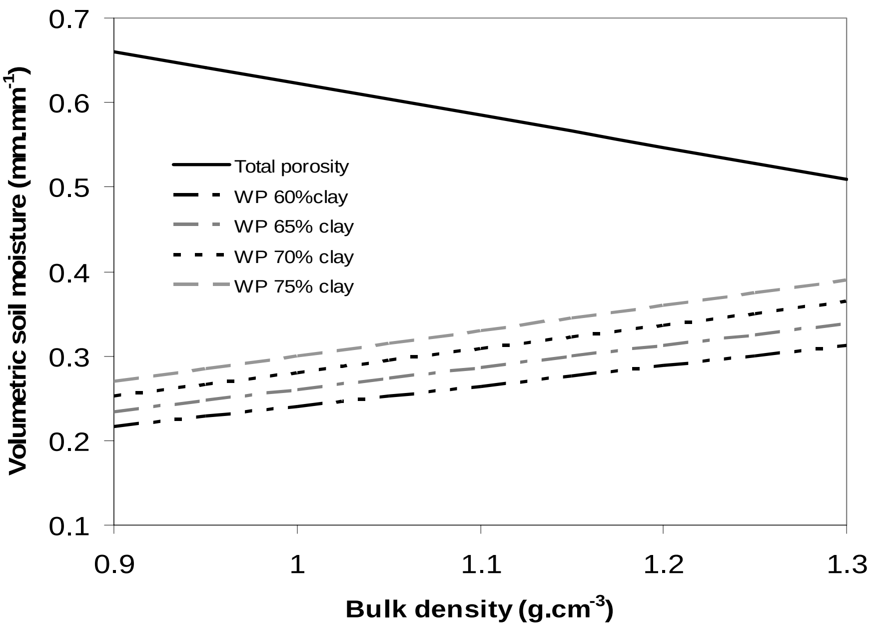
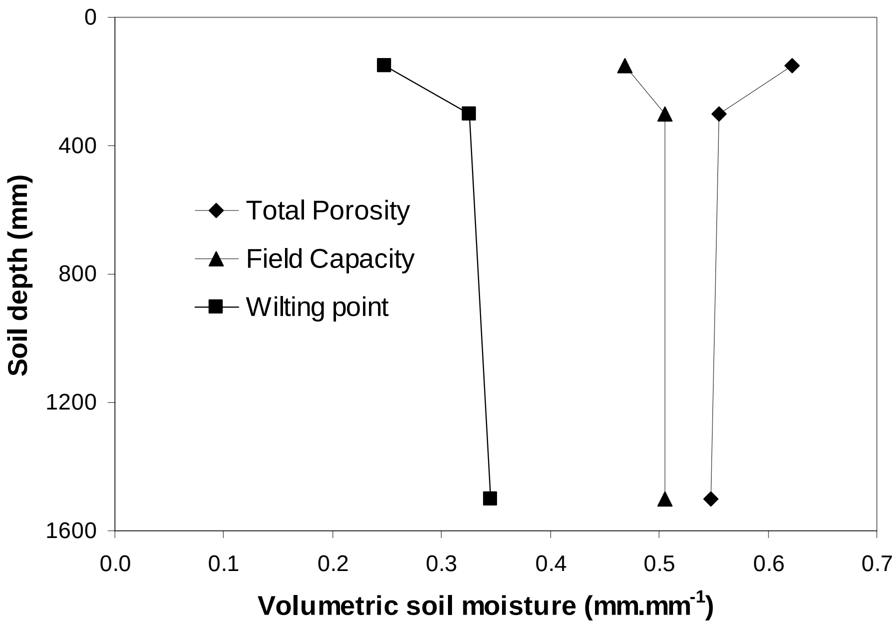


**Figure 10 : Volumetric moisture characteristics for soil depth profile as outputted from SWAT for an Irving clay.**




**Land use**

Land use for this study was classified by interpretation of aerial photography (2001) in conjunction with field investigations. A map of land use for Hodgson Creek catchment is shown in Appendix A, Map 5. The major land use for the catchment is dryland cropping of cereals, which accounts for about 51% of the total area. A further 45% of the area is used for grazing equally split between open pasture and wooded pasture with scattered trees. The remaining 4% of land use includes urban, rural-residential and road areas.

Default parameters for a range of land uses are provided with SWAT and these covered the land uses required for this study. Wheat, sorghum, pasture and evergreen forests were simulated while the small area of non-agricultural areas was not included in the analysis and this area was equally distributed into the other land use categories. Testing of the model to ensured realistic transpiration patterns, crop yields and surface cover were simulated for all land uses. Transpiration is important for catchment water balance in terms of timing and magnitude. The biomass production and cover are important because they provide inputs into algorithms dealing with erosion and herbicide transport.

**Climate data**

Climate data from 1950 to present was obtained from the SILO database (Jeffrey *et al.*, 2001) using the data drill method. This data is an interpolated data series that uses Bureau of Meteorology (BOM) records. The data set contained daily maximum and minimum temperatures, solar radiation, relative humidity and rainfall values. SWAT uses the closest climate station to the centroid of a sub-catchment and applies this climate to all HRU's for that sub-catchment The grid of data drill climate data sets used in the study are given as Appendix A, Map 1.

**Derived hydrologic response units**

The soils and land use layers were overlayed in GIS and a summary of their intersection is given in Table 7. They are presented from most frequent to least, left to right for land use and top to bottom for soils. The three most common soils, Charlton, Irving and Waco are all black cracking clays of varying depths and are frequently cropped. Forty percent of all land use in the catchment involved cropping on these heavy clays.

| Soil name | Land use | | | | Total |
|---|---|---|---|---|---|
| | Cropping | Pasture | Trees | Residential / Transport | |
| **Charlton** | 17.5 | 8.0 | 4.5 | 1.3 | 31.4 |
| **Irving** | 13.6 | 4.3 | 3.1 | 0.9 | 21.8 |
| **Waco** | 10.5 | 5.6 | 2.5 | 0.6 | 19.2 |
| **Kenmuir** | 3.6 | 3.0 | 5.4 | 0.2 | 12.2 |
| **Burton** | 4.9 | 3.8 | 1.4 | 0.5 | 10.6 |
| **Beauaraba** | 1.0 | 0.9 | 1.5 | 0.1 | 3.6 |
| **Glenmore** | 0.7 | 0.5 | 0.1 | 0.0 | 1.3 |
| **Total** | 51.7 | 26.2 | 18.5 | 3.6 | 100.0 |

**Table 7: Summary of soils and land use area ratio's (%) for Hodgson Creek catchment.**

### 3.1.2. Herbicide properties

There are two main properties that influence the movement of herbicide from its place of application. They are the herbicides persistence and sorption (Kookana *et al.*, 1998). Persistence refers to the amount of time it takes the chemical to dissipate in the environment and is usually described in terms of a half life.

The half life of a herbicide indicates how long it persists in the environment, with more persistent herbicides posing a relatively higher risk of “off site” loss than less persistent herbicide. The other property which determines transport pathway for herbicides is its tendency to adsorb to soil or organic material, often quantified by an adsorption coefficient. Highly adsorbed herbicides are preferentially transported with sediment and organics, while poorly adsorbed herbicides are transported as solutes in runoff water.

Atrazine and metolachlor have moderate persistence and sorption (Kookana, 1998), both of these properties reflecting their usefulness for application as a residual herbicides. These residual herbicides can persist in the soil environment and remain useful in controlling weeds for months after application. They are also soluble enough to be taken up by the roots of emerging weeds.

**Dissipation and degradation of herbicides in the environment**

Herbicide are dissipated and degraded by a number of processes in the environment. Initial losses at the time of application due to volatilisation can be significant, but this process is highly variable between herbicide applications (Betts, 2002). Physical degradation of herbicide in the soil environment can be affected by factors such as pH, temperature, and soil moisture conditions (Ferris *et al.*, 1989; Walker *et al.*, 1997). Dissipation of herbicides may be one of the most difficult processes to describe at a catchment scale and Leonard (1979) states that predicting the soil concentration of herbicide at any given point in time poses the greatest challenge to modelling herbicide losses.

In a review of herbicide properties for Australian conditions, the dissipation rates of atrazine from a number of studies are reported by Kookana *et al.* (1998). Table

8 shows the summary data from this review. It indicates that degradation rates can vary over an order of magnitude. The default half life values for atrazine and metolachlor in the SWAT database are 60 and 90 days respectively (Neitsch *et al.*, 2001). Local data (Rattray *et al*, 2007) suggest that the half life of atrazine may be as short as 20 days on vertosol soils.

| No. of soils and location | Soil Properties | | | Measured half life (days) | Source |
|---|---|---|---|---|---|
| | pH | Organic C (%) | Clay (%) | | |
| 4, NSW | n.a. | 0.72-1.45 | 37-78 | 50-68 | Swain (1981) |
| 2, NSW | 5.4-7.0 | 0.6-1.6 | 17-60 | 53-63 | Bowner (1991) |
| 2, NSW | 5.7-7.5 | 1.8-2.0 | 44-51 | 40 | Ferris *et al.* (1989) |
| 4, WA | 4.7-6.5 | 0.46-1.0 | 4-21 | 57-131 | Walker and Blacklow (1994) |
| 1, VIC | 8.5-9.4 | 0.7 | 1-26 | 62 | Stork (1977) |

**Table 8 : Summary of atrazine degradation studies conducted on Australian soils (Source: Kookana *et al.*, 1998)**

**Adsorption properties of herbicides in runoff**

The default $K_{oc}$ values for atrazine and metolachlor given in the SWAT database are 100 and 200 mLg respectively (Neitsch *et al.*, 2001). Local trial data for the vertosol soils (Rattray *et al*, 2007) suggest that a $K_{oc}$ of 100 for atrazine is suitable, however no data on metolachlor was collected in this study. A range of reported values for atrazine in Australian conditions are given by Kookana *et al.* (1998) and are presented in Table 9. In a separate review of the conservation tillage on pesticide runoff into surface water Fawcett *et al.* (1994) states that chemicals with $K_{oc}$ in the range 10-10,000 are primarily lost in soluble from in surface water runoff. Fawett *et al.* (1994) suggests that the transport of herbicides is less sensitive to this parameter than half life. For this study default values were considered suitable.

| No. of soils and location | Soil Properties | | $K_d$ (L/kg) | $K_{oc}$ (mLg) | Source |
|---|---|---|---|---|---|
| | pH | Organic C (%) | | | |
| 26, NSW | 4.3-8.1 | 0.3-6.0 | 0.24-8.4 | 70-219 | Bowner (1991) |
| 4, WA | 4.7-6.5 | 0.46-1.0 | 0.39-0.55 | 55-99 | Walker and Blacklow (1994) |
| 12, QLD | 5.3-8.4 | 0.7-1.8 | 0.6-4.4 | 75-377 | Walker *et al.* (1994) |
| 5, WA | 3.3-5.5 | 0.1-3.0 | 0.35-24.9 | 350-830 | Gerritse *et al.* (996) |

**Table 9 : Summary of atrazine sorption coefficients studies conducted on Australian soils (Source: Kookana *et al.*, 1998)**

## 3.2. OBSERVED SOIL AND WATER DATA

Three main sources of observed data were used for calibration and model testing. Two were paddock scale (1-5ha) trials of hydrology and water quality (Freebairn and Wockner, 1996; Rattray *et al*, 2007) and the third catchment scale (50,000ha) monitoring data (Rattray, unpublished data). It should be noted that while Bureau of Meteorology rainfall values were used for catchment scale modelling, for the paddock scale trials, measured rainfall data from trials were used in these simulation runs.

### 3.2.1. Paddock scale soils, runoff and water quality

The effects of cultivation management practices on runoff and erosion have been well characterised for the study area (Freebairn and Wockner, 1996) through a long term study site just outside the village of Greenmount (see Appendix A, Map 1). At this site a set of five contour bays, each about one hectare in size, were monitored over 16 years. Observations were taken of crop yield, stubble cover on the soil surface, soil moisture to 1.5 metres, rainfall, runoff and erosion. This is one of the most comprehensive studies of paddock scale hydrology undertaken within Australia and the results have become a benchmark to describe effects of conservation tillage on erosion. This study concluded that increased cover increases stored soil moisture, reduces erosion significantly and runoff to a lesser extent. The trial was mainly conducted as a winter cropping trial with four tillage treatment compared, but there are periods when summer sorghum was grown. The tillage treatments were stubble burnt, stubble incorporation, stubble mulching and zero tillage. One bay was put under pasture late in the trial. Details of the treatments are given in Table 10.

| Year | Bare fallow | Stubble incorporated | Stubble mulched | Zero till | Summer crops | Pasture |
|---|---|---|---|---|---|---|
| 1976 | 1 | | | | 2 | |
| 1977 | 1 | | | | 2 | |
| 1978 | 1 | | | | 2 | |
| 1979 | 3 | 4 | 1 | 0 | 2 | |
| 1980 | 1 | 3 | 4 | 0 | 2 | |
| 1981 | 4 | 1 | 3 | 0 | 2 | |
| 1982 | 3 | 4 | 1 | 0 | 2 | |
| 1983 | 1 | 0 | 4 | 3 | 2 | |
| 1984 | 3 | 0 | 1 | 2 | 4 | |
| 1985 | 2 | | | | | |
| 1986 | 2 | | | | | |
| 1987 | 4 | | 3 | | | 0 |
| 1988 | 1 | | 2 | | | 0 |
| 1989 | | | 2 | 1 | | 0 |
| 1990 | 3 | 1 | 2 | 4 | | 0 |
| 1991 | | | | | | 0 |

**Table 10 : Greenmount trial treatments by year and bay number each treatment was applied**

The HRU processes of the SWAT model were tested against the long term measured data set for Greenmount. Available data sets used for calibration of the model are described in Table 11. Records for the Greenmount study included all farm operations used during the trials for the period 1976 - 1991 which were utilised in setting up SWAT runs.

| Parameter | Data type |
|---|---|
| Rainfall | Continuous time series (daily) |
| Soil moisture to 1.5m | Measured 3-10 times per year |
| Crop yield | Measured for all crops |
| Surface cover | After runoff events and additionally 3-10 times per year |
| Runoff | Daily runoff |
| Erosion | Total erosion for each runoff event |

**Table 11 : Data set details for the Greenmount conservation tillage trials**

### 3.2.2. Paddock scale herbicide properties

A study of the dissipation rate and loss of atrazine in runoff from two five hectare contour bays was conducted on the Ridgeway family farm 'Cowarrie' (see Appendix A, Map 1), a commercial farm in the Hodgson Creek catchment, during the summer of 2001 (Rattray *et al*, 2007). The dissipation rate from the field work suggested a half life for atrazine of 20 days. This work suggested that the default sorption coefficient ($K_{oc}$) of 100 for atrazine was suitable for this study. The ability of SWAT to characterise the loss of atrazine in runoff was tested using this data set. Data sets used for input and calibration of the model are given in Table 12. Records for the Cowarrie study included all farm operations.

| Parameter | Data type |
|---|---|
| Rainfall | Continuous rime series |
| Crop yield | For all crops |
| Suspended sediment | Daily flow weighted for each runoff event |
| Soil herbicide | 7 samples through season |
| Herbicide loss in runoff | Daily flow weighted for each runoff event |

**Table 12 : Data set details for the Cowarrie herbicide transport trial**

### 3.2.3. Catchment scale runoff and water quality

**Streamflow**

The Hodgson Creek G.S. (see Appendix A, Map 1) has been in operation since 1987. The gauged record viewed as daily streamflow (Figure 11) shows the stream is highly ephemeral. Average annual streamflow for the gauged period was 54 mm/year with a standard deviation of 73 mm/year, maximum annual runoff was 242 mm in 1988 and the minimum was 0.2 mm in 1993. The period from 1987 to 1996 had significantly more runoff compared to the drier period experienced in the early 2000s. April and May have the highest average monthly streamflow (>6000 ML/month) over the period (Figure 12). Rainfall in these months is generally associated with widespread low intensity frontal systems. Calibration of the model was performed on monthly streamflow.

**Figure 11 : Daily Streamflow (Megalitres per day) at Hodgson Creek G.S. for the period May 1987 – June 2004.**

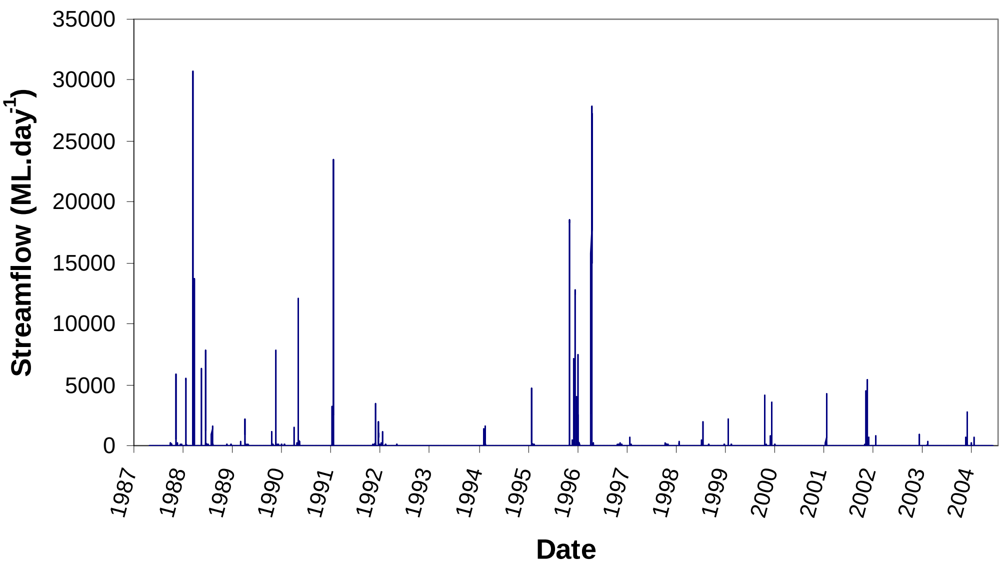
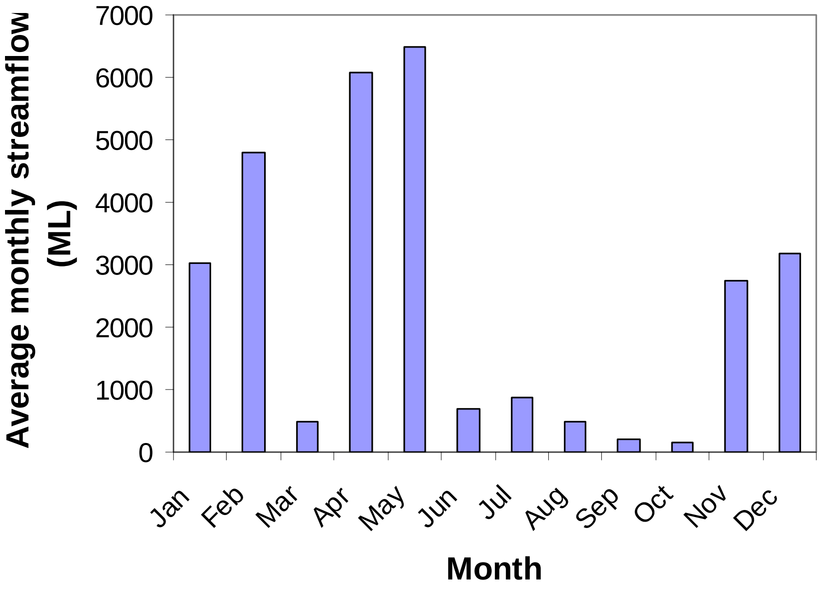


**Figure 12 : Average Monthly Streamflow (Megalitres) at Hodgson Creek G.S. for the period May 1987 – June 2004.**




**Water quality**

An ambient and event based water quality monitoring program ran for Hodgson Creek from 1999 to 2004 (Rattray, unpublished data). The ambient sampling consisted of monthly samples and during events daily sampling was undertaken. However within this period there is still limited data on high flow events due to drought conditions (as evident in Figure 11). Monthly loads of suspended sediments and herbicides for Hodgson Creek G.S. are presented as Figure 13 and Figure 14 respectively.

**Figure 13 : Monthly suspended sediment load at Hodgson Creek G.S. for the period 1999-2004.**

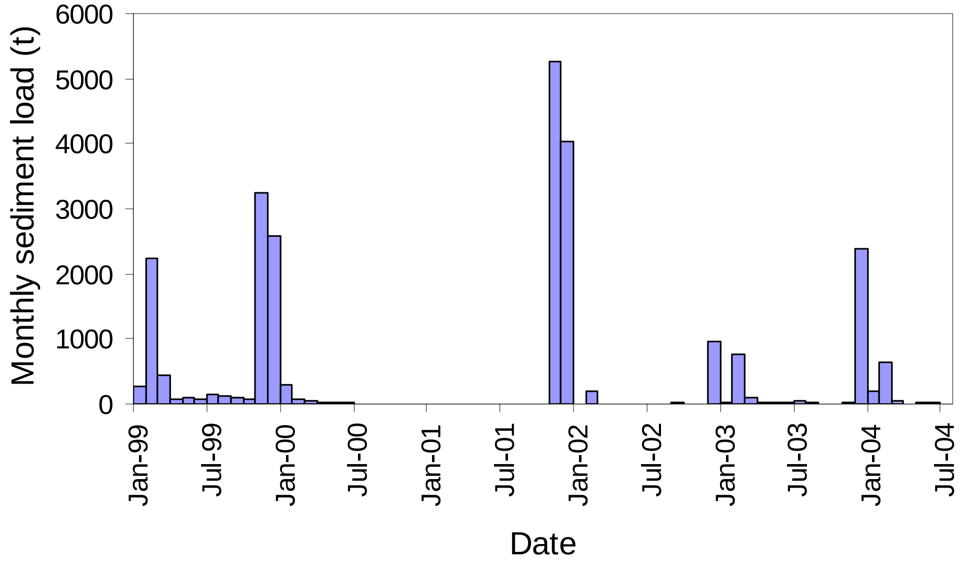
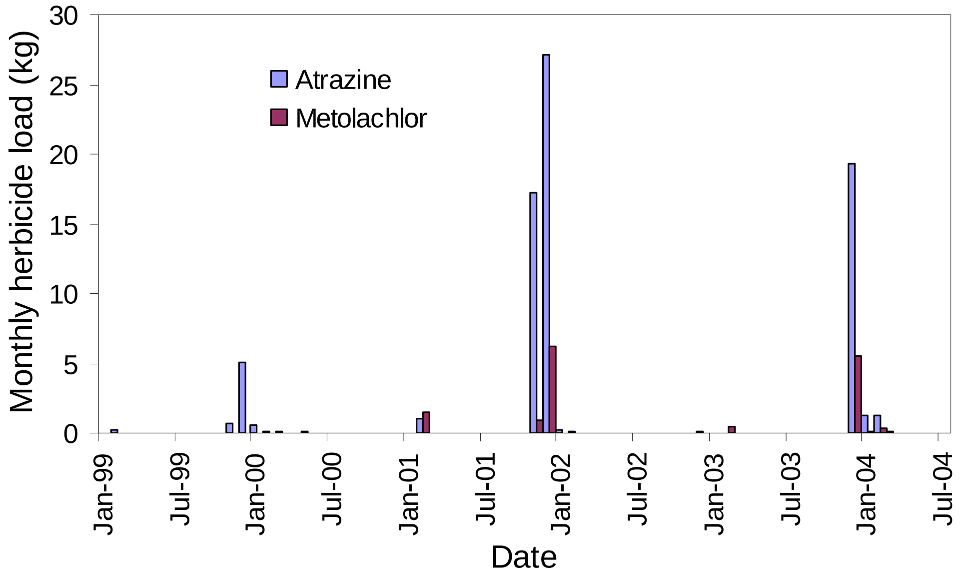



**Figure 14: Monthly herbicide load at Hodgson Creek G.S. for the period 1999-2004.**



## 3.3. PARAMETERISATION AND CALIBRATION METHOD

### 3.3.1. Parameterisation philosophy

SWAT was tested for its ability to represent processes important to predicting the generation and routing of runoff, suspended sediment and herbicide movement through Hodgson Creek catchment. Model testing was conducted for processes which were considered to be important to implementation of BMP (as outlined in section 2.5). This involved a subjective assessment of model processes through a visual inspection of model outputs where measured data was not available, and where measurements were available, testing the models ability to correspond with the observations.

As outlined in Section 2.2, SWAT operates as two distinct sub-models. Firstly the HRU scale model generates runoff and constituents and then streamflow and constituents are routed through a stream network. The method for calibration of SWAT proposed in the user manual (Neitsch *et al.*, 2001) is to calibrate against streamflow before fitting sediment and then herbicides. The logic of testing in a process dependence order is sensible, however the method proposed by Neitsch *et al.* (2001) assumes that the HRU processes are suitable and calibration only need consider catchment scale outputs. This study considered that the lack of HRU process testing had been a limitation in the literature and that it was imperative that the HRU scale processes operate adequately as a pre-requisite to a model producing adequate catchment responses. Parameterisation therefore requires confidence in HRU responses.

Where observed data was available to test HRU processes they were used in this project. This is in contrast to most other studies where little or no testing at the HRU scale is reported. Once confidence was gained in the generation of runoff and constituent, streamflow and water quality data at the gauging station would provide a point of truth for calibration of the delivery of pollutants through a catchment. The assumption was made that parameterisation of a model at the HRU scale would enable scaling up to sub-catchment scale. Implicit in this assumption is that a 1-5 hectare contour bay behaves similarly to a HRU which may three orders of magnitude larger (1000 ha). This scale effect is not considered significant for hydrology, however sediment delivery could be expected to be different between scales (Chen and Mackay, 2004).

Model investigations were investigated in a process dependant order similar to the method outlined by Neitsch *et al.* (2001). The principle is to calibrate in an order that accords with the processes description, i.e. for erosion to be calibrated the hydrology must be reliably calibrated first. Firstly, individual HRU were calibrated against paddock scale observations to ensure soil water, runoff, erosion and herbicide transport processes characterised. At this stage the model was also tested for its ability to predict the effect of paddock management practices on water quality outcomes, particularly erosion, sediment and herbicide generation. Secondly, calibration undertaken at the catchment scale was primarily concerned with delivery of the pollutants generated from the sub-catchment.

So calibration and testing of SWAT was an iterative process where observed data sets were used to fit the model for one component, then this "calibrated model" was used to test other components of the model. The underlying strategy was to first calibrate those components of the model that flow onto later order model outcomes. For example, it is not possible to calibrate a model for erosion if soil cover is not realistically modelled, as cover is a major driving input parameter into the erosion algorithm (Equation 2.9).

### 3.3.2. Calibration strategy

SWAT is a highly parameterised and complex model. Early in the study it became apparent that it would not be possible to investigate all components of the model and test all parameters for sensitivity. It appears from the literature that the generally accepted approach is to accept the default parameters provided with the model unless a good reason exists to do otherwise.

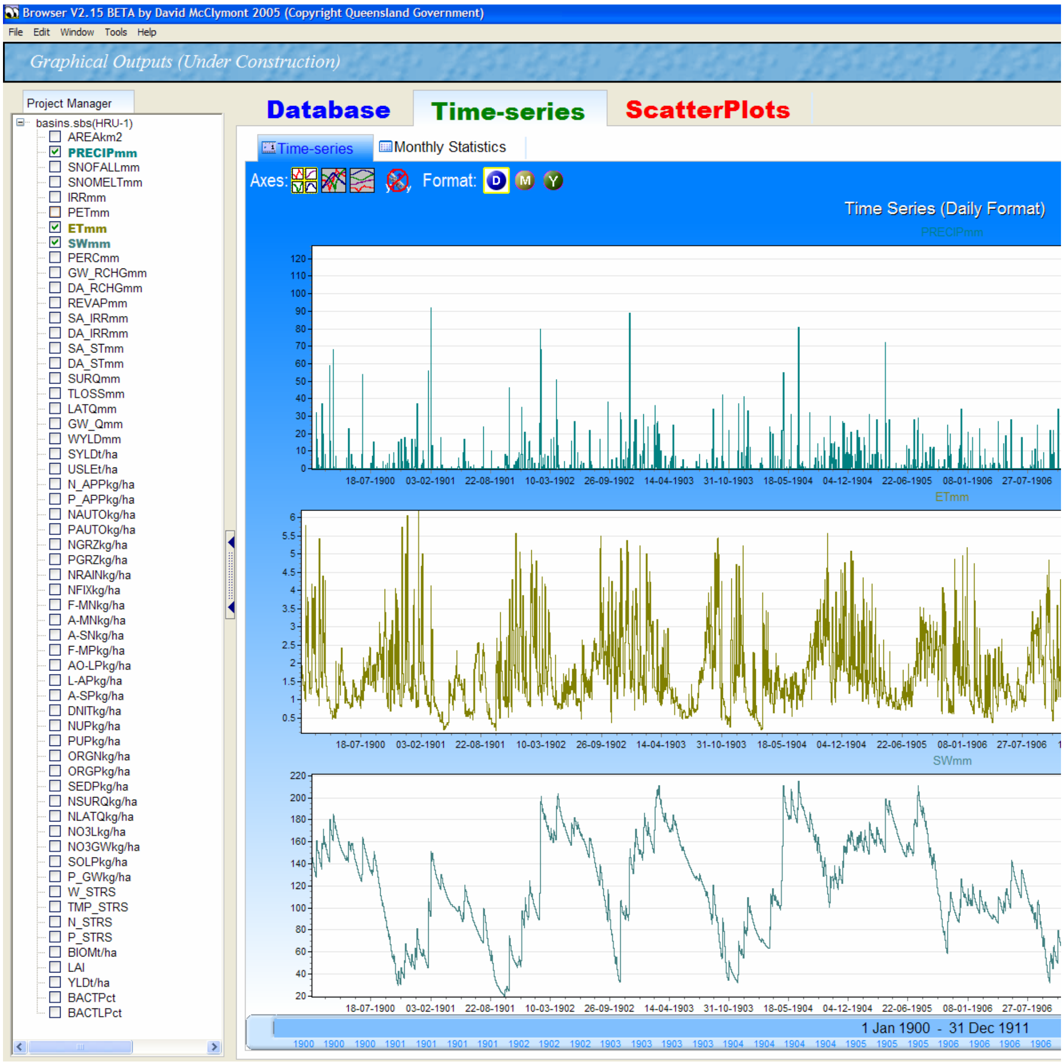
#### Useful tools in calibration

The ability to conduct detailed investigation of model processes was due primarily to two packages, Browser (McClymont *et al.*, 2001) and the Model Independent

Parameter Estimation (PEST) tool (Doherty, 2002). Browser is a time series analysis package where the considerable amount of model output generated by SWAT could be viewed efficiently.

A screen shot of daily rainfall, evapo-transpiration and soil water plotted using Browser is shown in Figure 15. Note that these three variable were selected out of a possible sixty output variables that can be viewed for one HRU. Browser allows the data to be converted to monthly or annual summary series and can provide statistics and scatter plots of observed and simulated data.

**Figure 15 : Screen shot of Browser (2.15) time series analysis tool.**



PEST is a parameter estimation package which allowed optimum parameter sets to be calibrated to match model output with observed field data using a nonlinear estimation technique known as the Gauss-Marquardt- Levenberg method. The strength of this method lies in the fact that it can generally estimate parameters using fewer model runs than any other estimation method (Doherty, 2002). In calibration mode PEST minimises an objective function comprised of the sum of weighted squared deviations between model outcomes and their corresponding field-measured counterparts.

Two particularly useful features of PEST that were used in the calibration of SWAT were, simultaneous calibration of multiple parameters and multiple objective functions, and an ability to fix relationships between parameters being calibrated. The multiple parameter, multiple objective function approach was used in calibrating paddock scale hydrology. By calibrating on soil water and runoff simultaneously, the inherent feedbacks of these two water balance components are captured. The ability to tie parameters was useful at the catchment scale where parameters across sub-catchments could be kept consistent. This method was also useful at the catchment scale to tie curve number of the different land uses together in a way that an order was maintained. This allowed a model to be optimised for streamflow by varying a range of curve numbers, yet maintained rules that certain soils and land uses behaved consistently.

**HRU calibration procedure**

The approach taken in choosing parameters for calibration for paddock scale processes was based on previous work by Littleboy et al. (1992b) (PERFECT), and Silburn and Freebairn (1992) (CREAMS). Calibration of the model was undertaken for HRU processes in the following order.

1. Investigated whether water use patterns (evapo-transpiration) were realistic.

2. Initial runs were undertaken using PEST to optimise against soil water data at paddock scale.

3. Initial runs of the model were conducted to test processes such as leaf area index (LAI), soil water and yield.

4. LAI was compared with other modelling projects (e.g. Owens pers. comm.) to get crop duration correct using PHU and LAI parameters (see Section 2.2.1).

5. Observed yield data for the range of treatments were fitted using Radiation use Efficiency and Harvest Index. Discussion with agronomist suggested that the "Cook" variety of wheat used in Greenmount trial is an older varieties with lower yield and harvest efficiencies of more recent variety and can have longer growing period to maturity.

6. The parameters of Residue Decay Rate and Biomass At Full Cover were used to calibrate cover levels. This calibration was primarily undertaken using the zero tillage treatment as these data suffer little interference from mechanical degradation of crop residue. In later calibration of the model some minor adjustments to residue decay rate for other tillage treatments were made where residue decay rates increase with increased tillage burial. Some minor adjustments to the affect tillage operations have on stubble cover were also made.

7. Soil water was then calibrated by using the Evaporation and Transpiration adjustment factors (EPCO and ESCO respectively) and a daily root growth parameter. These parameters adjust the rate to which water can be evaporated and transpired.

8. Curve number and saturated hydraulic conductivity for soils were used to calibrate runoff.

9. Erosion rates were checked using the USLE output of SWAT. These parameters are used as input into the MUSLE. USLE soil erodibility factor $K_{USLE}$ values are given by Loch *et al.* (1998) applicable to this study area. Cover and management factor $C_{USLE}$ factors have not been varied in this

study. USLE topographic factors $LS_{USLE}$ are generated by GIS and were adjusted to50 m to capture the affect that contouring has had on slope length.

10. Herbicide losses were checked against observed data but calibration was not attempted.

**Catchment scale parameterisation**

Calibration for the catchment scale processes were undertaken was considerably less involved than the HRU. The following steps were undertaken

1. The curve numbers derived at HRU scales were used a basis for guiding calibration at the whole of catchment scale. HRU combinations were calibrated by adjusting curve numbers using PEST to improve fit with observed runoff.

2. Sediment delivery was calibrated using the parameters which control peak flow rate and hence stream power.

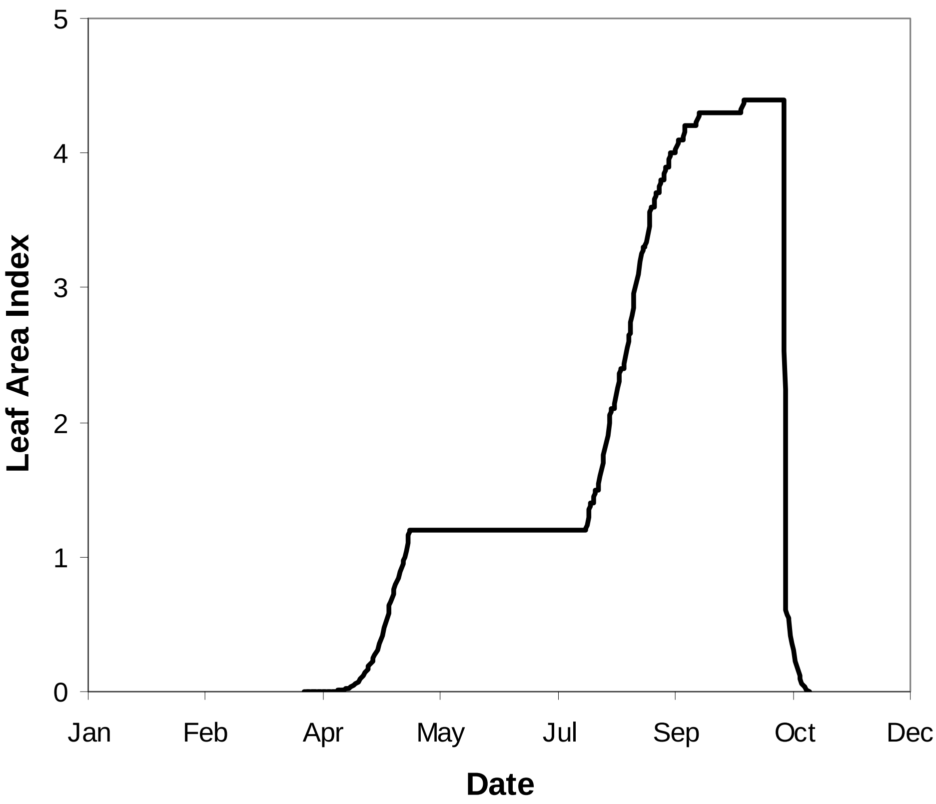
3. Herbicide runoff calibration at the catchment scale was not undertaken due to limited understanding of processes of delivery. The effect of application rate and timing of application of herbicides was tested as to its affect on herbicide losses.

### 3.3.3. Model modifications for this study

The SWAT2000 source code was provided with the SWAT program. The source code was in Fortran programming language and was re-compiled using a Lahey Fortan 90 compiler. This allowed a number of modifications to be made to the model including minor bug fixes. Outputs of SWAT were also able to put in a high precision format (to 7 decimal places, rather than the default 2) to allow resolution of the inverse algorithm method in PEST. The files modified for PEST were the HRU (.sbs) output files and the sub-catchment outlet (.swt) output files and outputted as e14.7 format.

The plant growth model in SWAT allows crops to have a dormant phase. The trigger for dormancy is day length, such that when a calculated day length is below trigger length dormancy is enacted. Day length is varied in the model by longitude. A problem was encountered during the modelling where wheat became dormant during winter which is not observed in a sub-tropical environment. An example is given inFigure 16 of the effect of dormancy on crop growth where the crop does not accumulate LAI. Of most concern was that during the dormant period no transpiration is modelled reducing the ability of to model to adequately describe soil water dynamics. To correct this problem, the dormancy feature for cold annuals was deactivated.

**Figure 16 : Leaf area index patterns modelled by SWAT for a wheat crop when dormancy is active, where the dormant phase runs from late April to early July.**




Similarly the pasture model in SWAT includes a dormancy phase. As pasture dormancy does occur in study area it was retained in the model. It is noted however that pasture dormancy in the study area is associated with low temperature and not short day length, although the two are correlated. In SWAT at the start of dormancy for pastures the model converts a percentage of green matter into residue cover. Based on GRASP modelling (Owens pers comm.) this conversion ratio was set at 70%, such that at dormancy onset 70 % of green matter biomass is converted to residue biomass.

To better understand model function and too be able to compare model output to observed data sets that were available, additional parameters of residue and total cover, above grown soil cover, total porosity, soil water at saturation, soil water at field capacity, and soil water at wilting point were outputted.

All modification to the code change made are given in Appendix B. Code change authors. DJR – Danny Rattray. DPI&F, Toowoomba; JYY – Jo Owens, DNRM, Toowoomba; JD – John Doherty, Watermark, Brisbane.

# CHAPTER 4. RESULTS

This chapter presents results of model testing and calibration of SWAT. Where observed data was not available for calibration, model outputs were checked to ensure they appeared realistic for local conditions. HRU processes were calibrated against observed paddock data sets and parameters derived from HRU parameterisation process were used in catchment scale calibration.

## 4.1. MODEL PERFORMANCE AT PADDOCK SCALE

The following section presents the calibration processes against observed data available for hydrology and erosion (Greenmount, 1 ha), and for herbicide transport (Cowarrie, 5 ha) (see Section 3.2.1).

### 4.1.1. Vegetation processes

**Wheat cropping and the effect of tillage management**

This section describes calibration of SWAT HRU parameters for winter wheat cropping and testing of the models ability to predict the effect that tillage management has on hydrologic and erosion outcomes.

Leaf area index (LAI) patterns from SWAT, which effect crop water use and biomass production, were checked against the PERFECT (Littleboy, 1989) model which has been tested for local data. The number of heat unit to achieve crop maturity and the maximum LAI were adjusted manually until a fit was achieved between the two modelled curves.

The model was then tested to check wheat yields against observed data from the Greenmount trial. The model achieved good fits with observed data as shown in Table 13, using a harvest index of 0.3. Observed yields would have a measurement error of ± 0.2 t/ha and all modelled yields fall within this range, with the exception of the zero tillage treatment. It should be noted that during the period the observed data was collected many challenges in zero tilled wheat, particularly an ability to plant satisfactorily into high cover situations may have resulted in sub-optimal yields.

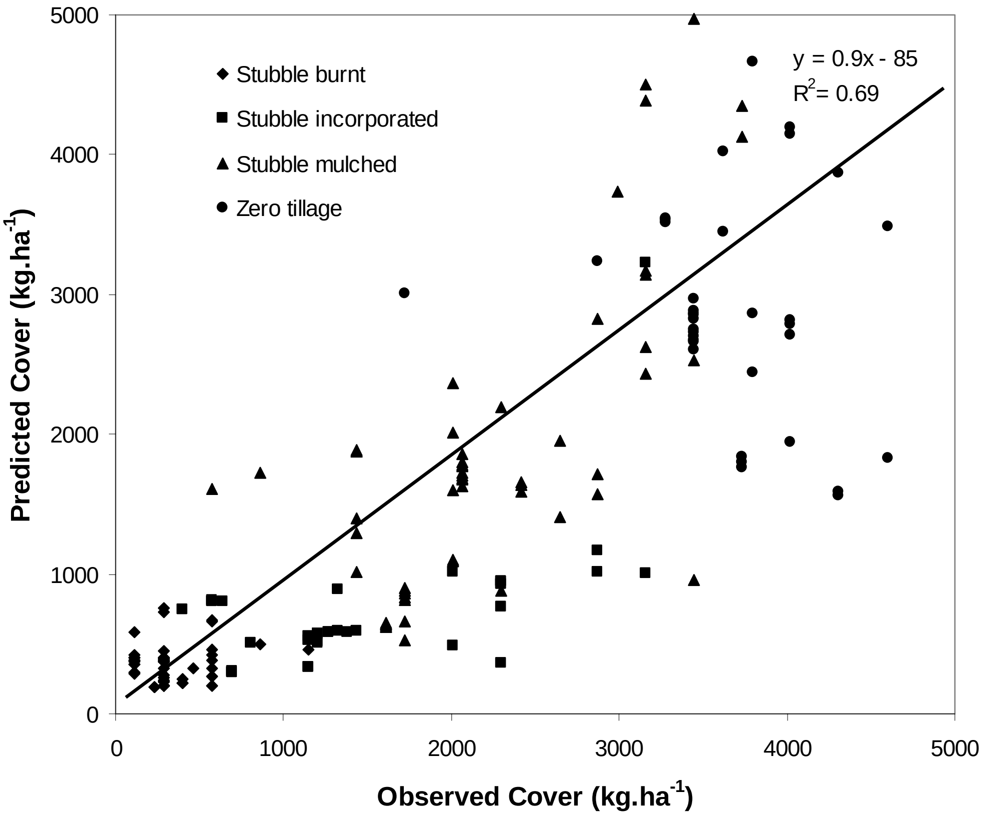
| Tillage treatment | Bare (Burnt) | Incorporated | Stubble mulched | Zero till |
|---|---|---|---|---|
| Observed (1979 – 1983) | 2.8 | 2.8 | 3.1 | 2.8 |
| Predicted (1976- 1992) | 2.7 | 2.8 | 3.0 | 3.1 |

**Table 13 : Observed and predicted wheat yields (t/ha) for a range of tillage treatments**

The model was tested for its ability to estimate surface residue cover. Surface residue is the remaining biomass after removing crop yield. This surface stubble will degrade with time. Observed data from the range of tillage treatments was compared with the modelled tillage treatments simultaneously and the results are given in Figure 17. The parameters varied to improve model performance were the stubble degradation rate and the amount of stubble removed due to tillage passes, with the latter varied only slightly. When all cover data was plotted up, it is seen that SWAT was able to model cover levels over the full range from bare to high cover well. SWAT does not output surface cover (%) and that was the format of the observed cover. This required observed covers to be converted to an equivalent biomass on the surface using cover using an algorithm from PERFECT (Littleboy, 1989). Where;

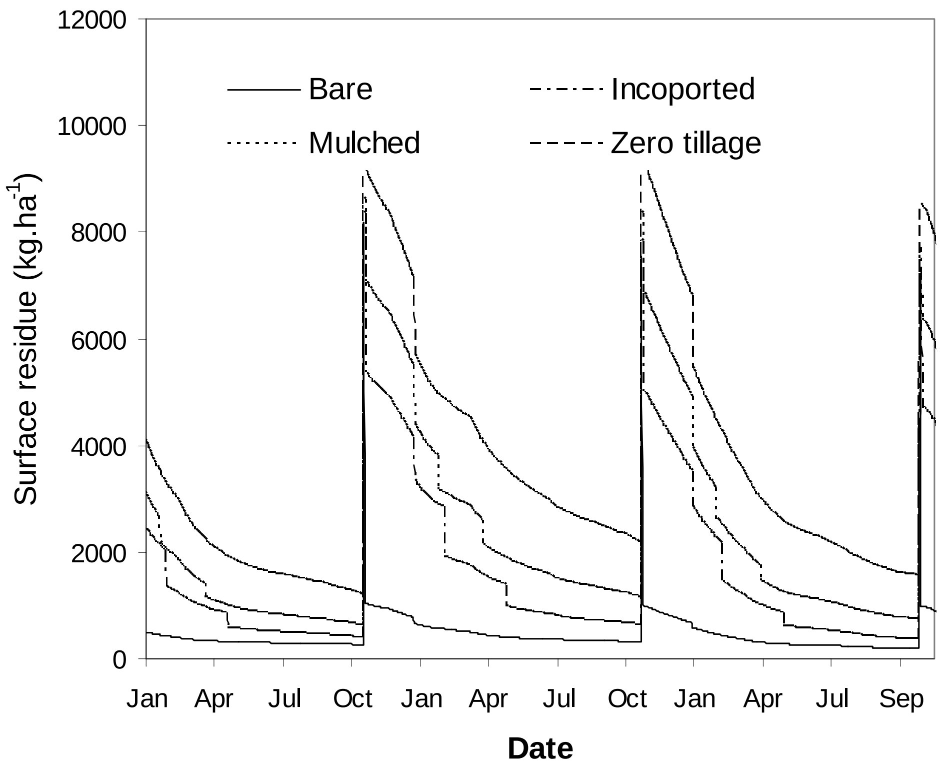
**Cover (%) = cover (kg/ha) / 6000** **(4.1)**

**Figure 17 : Observed vs. predicted covers (%) for wheat stubble for a range of tillage treatments.**




Time series dynamics for surface cover for a two season's period is shown in Figure 18. It can be seen that higher tillage treatments are retaining less cover than low tillage treatments. Unfortunately there appears to be a problem on January 1 where a fraction of the stubble is degraded for no apparent reason in all treatments. Investigation of the model code was unable to resolve the reasons for this error. It was suspected that this error may represent a discontinuity due to SWAT using a combination of dates and day counts after operations to derive model outputs on a daily basis.

**Figure 18: Time series surface cover (kg/ha) for a range of tillage treatments**

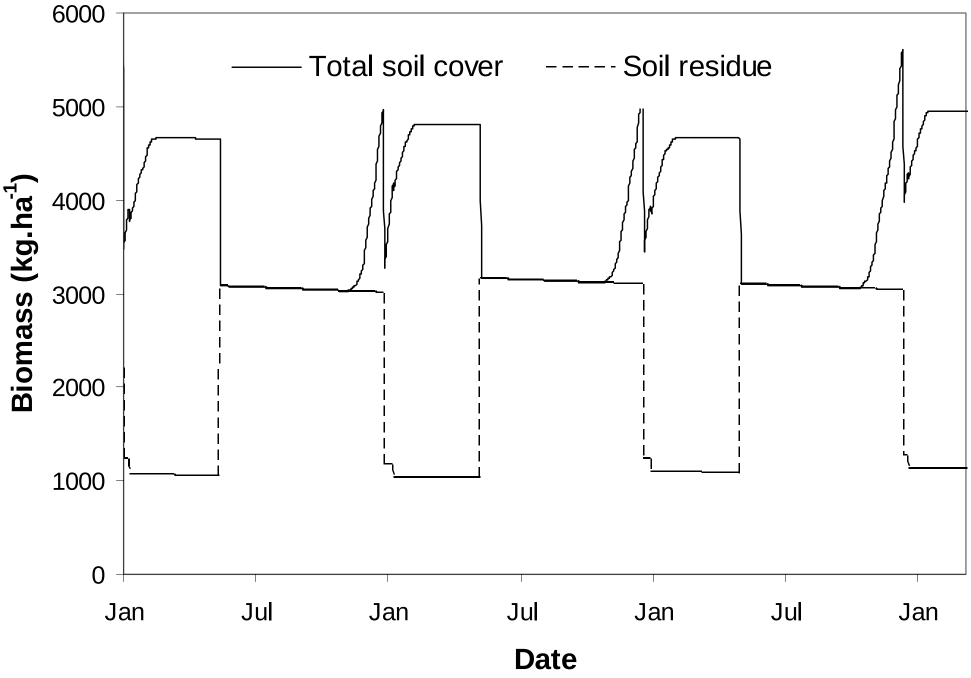



**Summer cropping – sorghum**

While the Greenmount trial had a summer cropping component, there was little consistency in regard to crop type and tillage. Other issues such as failed crops make the data set difficult to use in this modelling exercise for comparative purposes.

In SWAT, paddock operations can be defined by a date on which they occur or by using a heat sum approach. The latter being similar to PHU required for a crop to reach maturity (see Section 2.2.2). Summer cropping in Australian typically results in crops growing over the end of a calendar year. Testing of the sorghum model in SWAT identified that using the dates method resulted in model errors for summer crops. Using the heat unit method allowed summer crops to grow over a calendar year boundary. However the sorghum component of SWAT still gave erroneous results for surface residue as shown in Figure 19.

**Figure 19: Modelled sorghum surface and residue cover showing model errors associated with the end of the calendar year.**



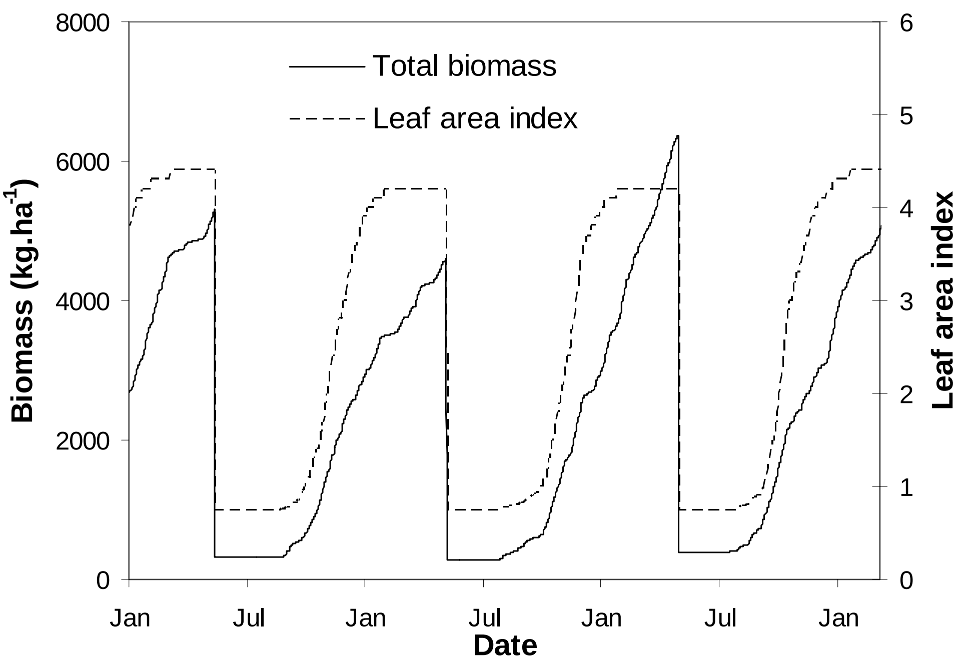

**Pastures**

A significance difference between SWAT and locally developed pasture models such as GRASP (Littleboy and McKeon, 1997) is that dormancy in SWAT is determined by day length, while in Australia it is associated with low temperature. Testing of the model showed that using day length was able to provide satisfactory results for this modelling exercise for water balance components as shown in Table 14 and Table 15. However further testing of the pasture model would be required if SWAT as to be used to test pasture management scenarios. It would be more satisfying if SWAT responded to the real physiological drivers in Australia, rather than 'trick' the model into behaving realistically, however it is not a major limitation to the application of the model in this study.

**Forests**

SWAT was unable to accurately describe LAI and biomass dynamics for forest land use (Figure 21). This problem was also described by Watson el al (2003), and has to do with loss of leaf area being more representative of deciduous species, while leaf drop for Australian species is generally associated with drought. However the limitation described does not pose a major limitation to the application of the model in this study. However, if forest management were a consideration for scenario testing, or the area under forests were to be changed further testing of this component of SWAT would need to be considered.

**Figure 20: Leaf area index, biomass for forest land use as modelled by SWAT**




**Hydrology**

Having tested and parameterised the plant model component, the strategy was then to attempt calibration of the hydrology. Soil water and runoff for all treatments were calibrated simultaneously using PEST. This made it possible to automate the calibration process and simultaneously calibrate the four wheat crop tillage treatments.

The two variables modified were the soil water use factors for evaporation (ESCO) and plant water use (EPCO). Both parameters modify the ability for potential evapo-transpiration demand to be met by adjusting the depth to which water is accessed in a soil profile. The parameters vary between 0 and 1, with 1 being the default and the as the number decreases demand from lower in the profile is allowed. The results of calibration were ESCO did not vary from 1, however the EPCO was fitted to around 0.9. The daily root length growth was not adjusted.

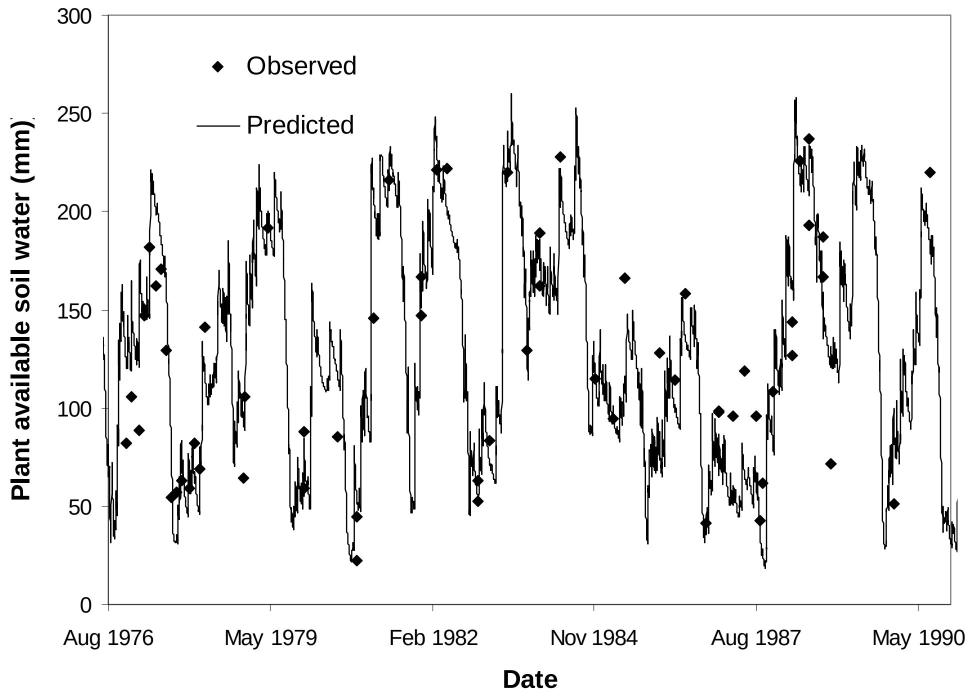
It should be noted that the calibration of soil water parameters did not vary soil water dynamics significantly from the initial runs used for testing crop yield and residue cover. The resulting fits against observed soil water data are shown in Table 14. Results of curve number calibration against observed runoff and curve numbers derived are shown in Table 15.

Figure **21** shows the time series observed and predicted plant available soil water for wheat with a bare fallow treatment.

| Tillage treatment | Bare (Burnt) | Stubble Incorporated | Stubble Mulched | Zero tillage | Pasture |
|---|---|---|---|---|---|
| $R^2$ for 1:1 (Obs. vs. Pred) | 0.81<br>(n= 58) | 0.76<br>(n= 24) | 0.71<br>(n= 22) | 0.69<br>(n= 18) | 0.80<br>(n= 22) |

**Table 14 : $R^2$ for observed Greenmount trial data versus predicted soil water for a range of tillage treatments.**

**Figure 21: Time series of observed and predicted soil water for Greenmount wheat, bare fallow (1976-1990)**




Runoff was calibrated simultaneously with soil water and the model demonstrated an ability to predict daily runoff well ($R^2$ ranging from 0.65-0.76). For each treatment the curve number was calibrated independently. The bare plot had the highest curve number and zero tillage the lowest curve number. The results are similar to those achieved by Littleboy *et al.* (1992a).

| Tillage treatment | Bare (Burnt) | Stubble Incorporated | Stubble Mulched | Zero tillage | Pasture |
|---|---|---|---|---|---|
| $R^2$ for 1:1 (Obs. v Pred) | 0.76 (n= 73) | 0.65 (n= 42) | 0.66 (n= 59) | 0.70 (n= 43) | 0.70 (n= 12) |
| Curve number | 84 | 79 | 70 | 65 | 73 |

**Table 15 : $R^2$ for observed Greenmount trial data versus predicted daily runoff and curve numbers for a range of tillage treatments.**

**Erosion**

A major effect of tillage management is the stubble cover during the fallow period. This cover is significant in its ability to reduce hillslope erosion (Freebairn *et al.*, 1986). Hillslope erosion rates from the observed data were compared with the USLE outputs from SWAT and are shown in Table 16 and show good correlation with a maximum error around 30% in predicting the long term average.

| Treatment | Burnt | Incorporated | Stubble mulched | Zero till |
|---|---|---|---|---|
| Predicted average erosion (t/ha) | 30.2 | 9.4 | 6.9 | 2.7 |
| Observed average erosion (t/ha) | 42.8 (n= 78) | 11.6 (n= 46) | 7.4 (n= 60) | 1.8 (n= 46) |

**Table 16 : Observed as predicted erosion for a range of tillage treatments (1976-1990)**

The sorghum model was also tested for erosion outcomes and the model predicted of 16 t/ha/annum and 15 t/ha/annum, for conventional tilled sorghum and zero till sorghum respectively. These results are unrealistic and suggest a structural problem with the model associated with summer cropping, as mentioned in crop model testing earlier, and this limits the ability of the model to adequately represent the impact that tillage has on this cropping system.

#### 4.1.2. Hydrology and erosion

The calibrated model was used to make water balance and erosion predictions for various land uses and land management practices using a long time series of climate (Greenmount, 1901-2001) (presented in Table 17). These predictions offer a comparison of a range land uses and tillage treatments, and give an example of the opportunity to use SWAT as a tool for making comparative assessments at the HRU scale. Of note in this comparison are:

- Water excess under wheat systems to be similar for various tillage types (68-73 mm/annum) and shows that as tillage is decreased the runoff also decreases and drainage increases,
- Water excess under the sorghum, trees and pastures treatments was between a half and a quarter (35, 15 and 17 mm/ annum) of wheat systems,
- Erosion for trees and pasture were significantly lower than both cropping scenarios.
- Erosion was reduced by 90% for zero tillage wheat as compared to stubble burning.

.

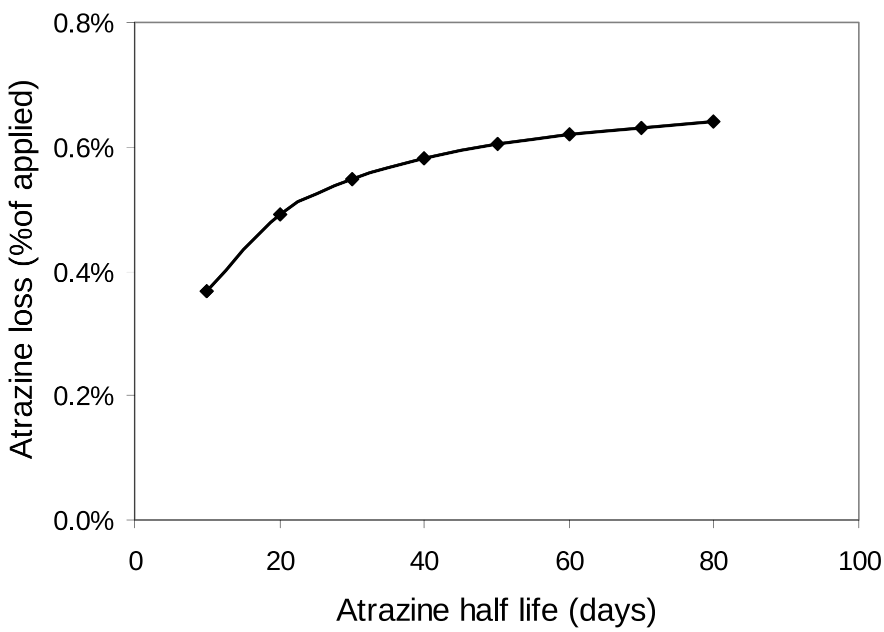
| Treatment | Wheat Stubble Burnt | Wheat Stubble Incorporated | Wheat Stubble mulched | Wheat Zero till | Sorghum Stubble Incorporated | Forest | Pasture |
|---|---|---|---|---|---|---|---|
| **Rainfall (mm)** | 713 | 713 | 713 | 713 | 713 | 713 | 713 |
| **Evapotranspiration (mm)** | 646 | 650 | 648 | 643 | 685 | 706 | 704 |
| **Runoff (mm)** | 68 | 53 | 35 | 32 | 25 | 12 | 13 |
| **Drainage (mm)** | 5 | 15 | 32 | 39 | 10 | 3 | 4 |
| **Excess water (mm) (Runoff + Drainage)** | 73 | 68 | 67 | 71 | 35 | 15 | 17 |
| **Average Annual Erosion** | 28.1 | 9.9 | 5.2 | 2.6 | 16.5 | 0.2 | 0.2 |

**Table 17 : Annual average water balance and erosion for a heavy black clay soil (Irving) with Greenmount climate( 1901-2001) for a range of land uses and management scenarios.**

#### 4.1.3. Herbicide processes

Since there was some uncertainty in herbicide half life values, the affect that half life had on annual herbicide loss was tested and the results are shown in Figure 22. The variability of half life of atrazine shown in Table 8 suggests that where local data exists it should be used in preference to default parameters. Local field trials for atrazine suggested a half life of 20 days. The results showed a 25% reduction in herbicide loss when half life was decreased from the default of 60 days to locally measured 20 days.

**Figure 22: Herbicide loss sensitivity to half life scale**

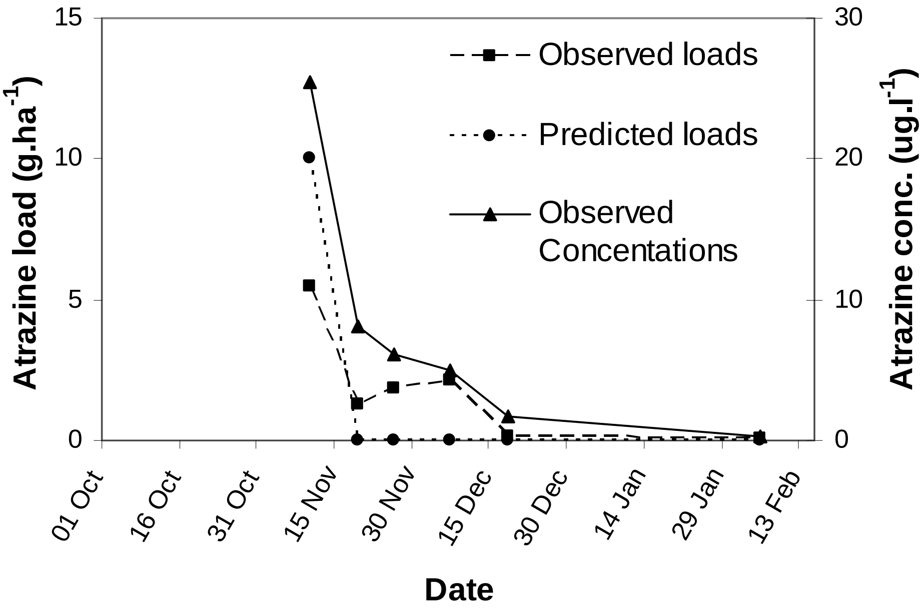



While data were available on herbicide concentration in runoff at paddock scale, SWAT does not output paddock scale (HRU) concentrations of herbicides. It should be noted that this only became apparent during model testing and it was earlier assumed that SWAT would provide daily concentrations as Neitsch *et al.* (2002) provide an example of daily herbicide concentrations using SWAT. The option of changing the software code to output herbicide concentrations were not feasible within the current software structure. Herbicide loads delivered from the

HRU can be viewed at the reach (.rch) for a daily time step and the total annual load for a sub-catchment can be viewed in the output.std file. The first step in testing the model was to compare annual losses. A SWAT model was created to simulate the Cowarrie trial (Rattray *et al*., 2007). Herbicide losses were predicted to be just under 0.4 % for the 2000/01 season, with greater than 90 % lost in the solute form. Observations at the Cowarrie study were around 0.4 % for the same season. The Cowarrie data also showed greater than 90 % of the atrazine lost was in the soluble phase. These results compared well with results from other models that put paddock scale annual losses of herbicides at generally less than 2 % (Kookana *et al.*, 1998).

While the model predicted the total loss for the season correctly, the temporal pattern of loss was different between the model and observed as seen in Figure 23. The model predicted only one runoff event generating herbicide losses. After this first event, subsequent runoff events showed no herbicide losses. Observed data showed a tapering off of concentration (and loads) throughout the season with a steady decline associated with the dissipation of chemical in the soil. This is a considerable difference and implies that the model will only generate a herbicide load for the first runoff event after herbicide application.

**Figure 23: Observed and predicted atrazine loads and Observed atrazine concentrations (Cowarrie, atrazine applied at 2.5kg/ha active ingredient applied 1 October 2001)**




#### 4.1.4. Herbicide losses as affected by application of best management practices

While the model had demonstrated a low performance for characterising the temporal loss process for atrazine, the total loss for a season was good. It was therefore considered appropriate to test the application of best management practices in the model to compare the effectiveness of the various treatments on total seasonal losses. This testing was conducted using the Cowarrie model set up and a 50 year (1950-2000) data drill climate file for this location.

**Reducing soil herbicide input through reduced application rate**

The model showed a linear response between herbicide level and application rate. Halving or doubling application had a corresponding effect on the herbicide lost.

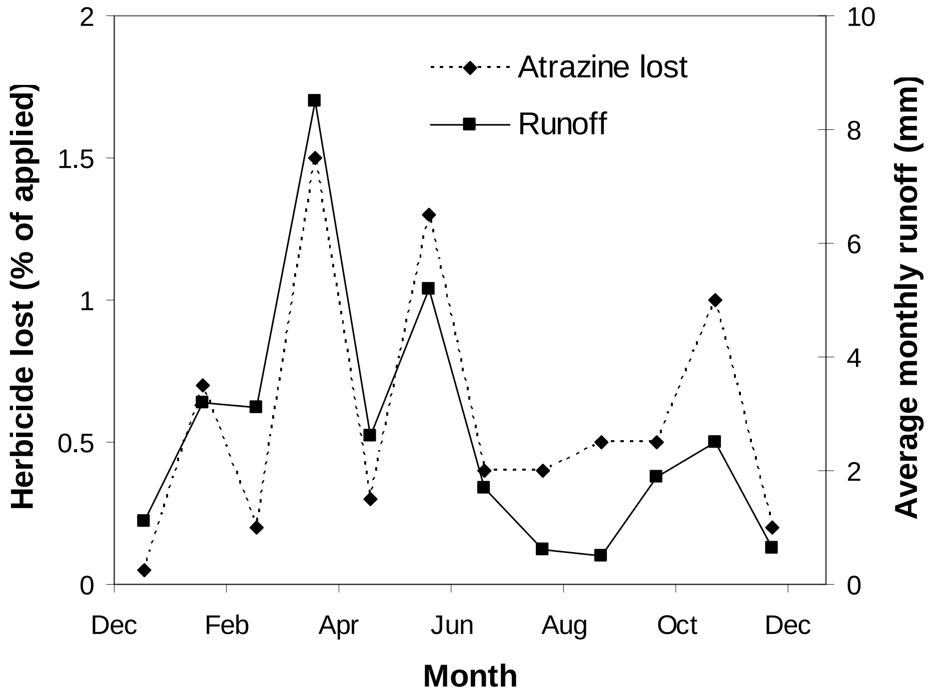
**Effect of incorporation**

Tillage of the soil a day after herbicide application was explored as a management practice to reduce herbicide loss. The concept is that incorporation of a chemical to deeper in the soil profile results in reduced surface concentration of a chemical. A tillage to 25 cm resulted in total herbicide lost decreasing from 0.5 % to 0.1 %, showing that the model predicts this practice to be effective in reducing herbicide loss.

**Time of application.**

SWAT was able to explore dynamics of herbicide movement associated with runoff and erosion through the year. The months of April and June when runoff was the highest are also associated with the highest loss of herbicide when the chemical application is set for this month.

**Figure 24: Atrazine lost (% of total application) with application date varied by month.**




**Filter strips on edge of paddock**

SWAT allows an edge of paddock filter to be included at HRU level. Model input is simply the width of the filter to be incorporated. SWAT was run, to compare the filtering capacity of a range of filter widths effect on herbicide delivered to a stream reach. Scenarios are compared with a base case scenario of no filter are given in Table 18. The model predictions showed a remarkable capacity to filter atrazine, with reductions of 60% for a 5m filter and 90% for a 20m filter. These predictions are not able to be tested for Australian conditions due to lack of observed data.

| Filter width (m) | 1 | 2 | 5 | 10 | 20 |
|---|---|---|---|---|---|
| Filtering capacity (%) | 35% | 50% | 60% | 75% | 90% |

**Table 18: Filtering capacity of a range of edge of paddock filter widths.**

## 4.2. MODEL PERFORMANCE AT THE CATCHMENT SCALE

### 4.2.1. Runoff

PEST was used to calibrate SWAT using observed runoff from the Hodgson Creek G.S. for the period 1988 -2003. Calibration was achieved by adjusting the SCS cure number as suggested by Neitsch *et al.* (2001). A curve number of one unit higher than derived for the annual crops and a curve number of 73 for the pastures and trees were derived. Monthly observed and predicted runoff is shown in Figure 25. The coefficient of determination was $R^2$ = 0.92 as shown in Figure 26.

**Figure 25 : Observed and predicted monthly flows at Hodgson Creek G.S.**

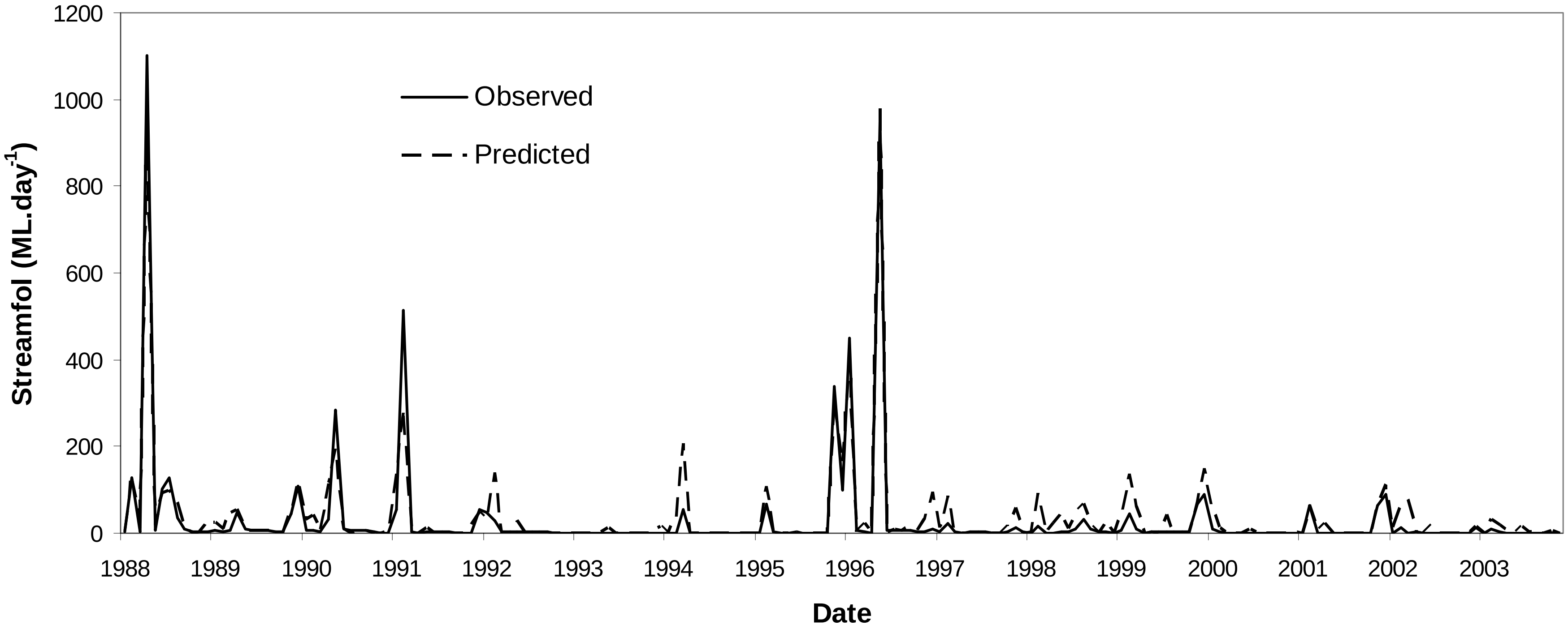
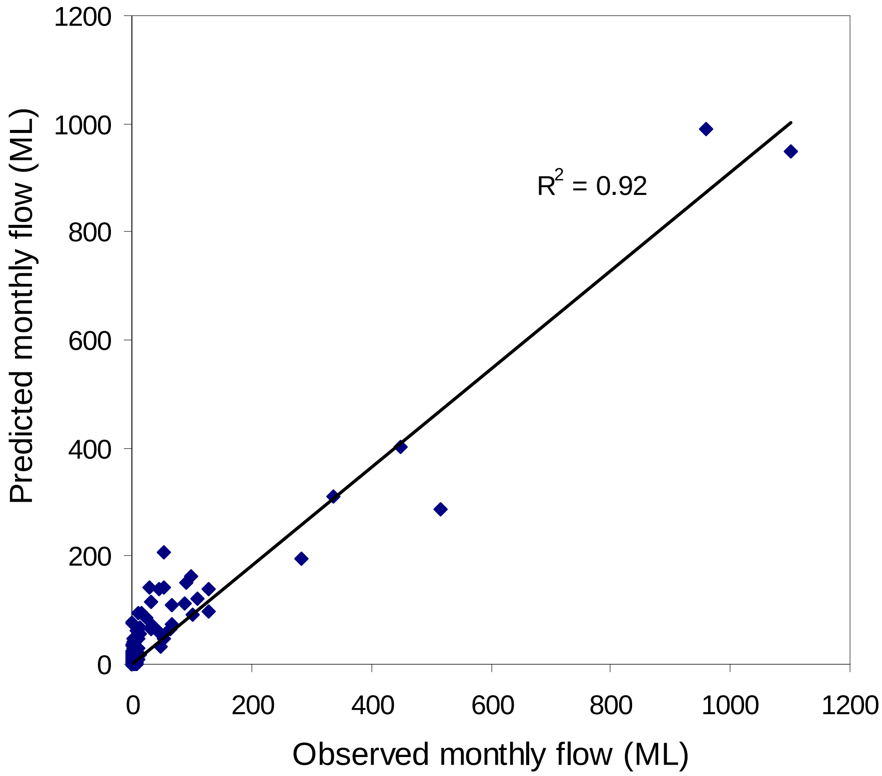


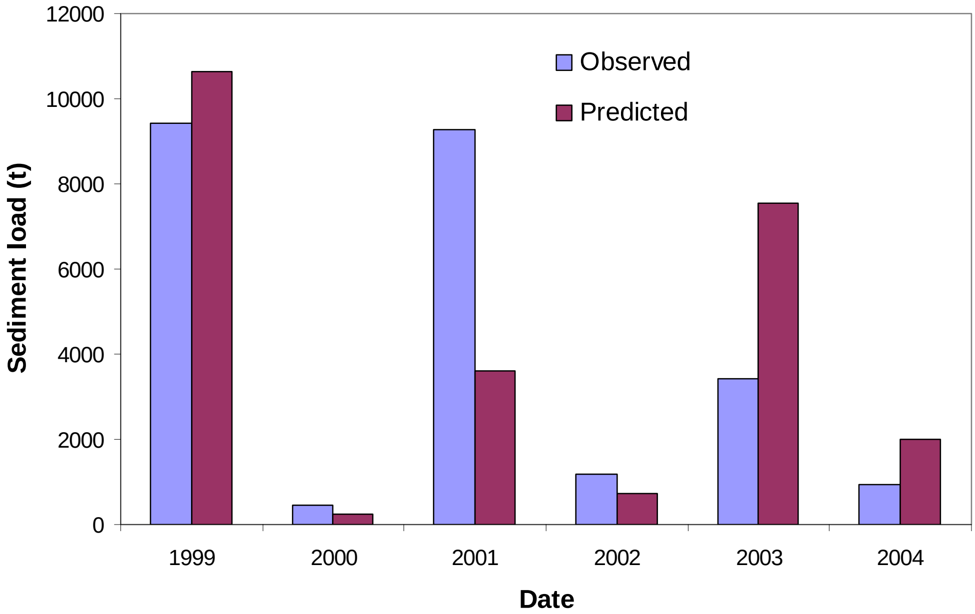
**Figure 26 : Scatter plot of observed and predicted monthly flows at Hodgson Creek G.S.**




### 4.2.2. Suspended sediment

Having achieved a good representation of the hydrology on a monthly basis (Figure 26), the model was then tested for its ability to predict annual sediment loads. Calibration was achieved by manually adjusting the peak rate adjustment factor (from Equation 2.12), as suggested by Neitsch *et al.* (2001) until an average annual load of 4,950 tonnes was achieved for the calibration period 1999-2004. A peak rate adjustment of 0.5 was used to achieve the results shown in Figure 27. The root mean square error for annual predictions was 2900 tonnes, or 67% of the average, and mean absolute error was 72%.

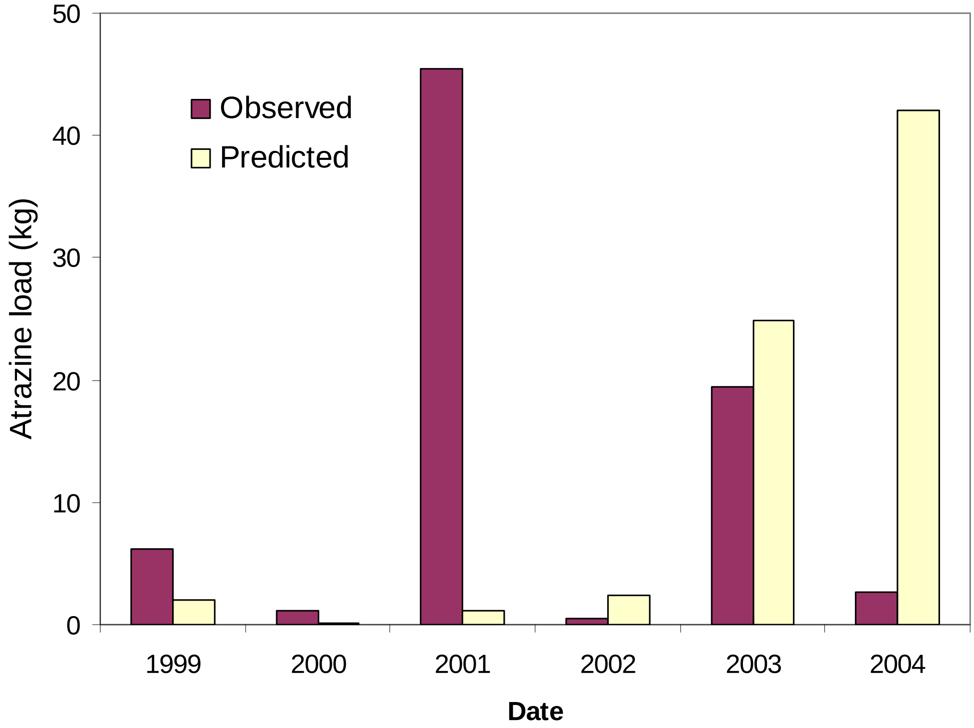
**Figure 27: Observed and predicted annual sediment loads at Hodgson Creek G.S.**




#### 4.2.3. Herbicides

Since SWAT had provided a good representation of the hydrology and sediment yield, the model was then tested for its ability to predict annual atrazine loads for the observed period of 1999-2004. Atrazine application was set using the heat sum method to occur shortly before planting in early October. The rate of application was adjusted until an average annual load of 15.1 kg was reached to match the observed data. The results of the model run are shown in Figure 28. It was noted that the model was performing poorly and an attempt to improve model performance was made by trying various planting and herbicide application date. However the result of this testing process was that the model was observed to respond varied erratically (not shown here). This is consistent with the HRU testing of the herbicide loss process that showed responses that were not consistent with our understanding of the process. With the model performing poorly model testing was terminated at this stage.

**Figure 28: Observed and predicted annual Atrazine loads at Hodgson Creek G.S.**



# CHAPTER 5. DISCUSSION

The objectives of this study were to determine the suitability of SWAT:

1. To represent processes important in predicting generation and routing of runoff, suspended sediment, and herbicide at both paddock and catchment scale; and

2. As a tool for use in water quality assessment and planning processes.

The discussion of the study findings regarding these objectives is made in four parts. The first objective is discussed by way of a general summary of how the model performed and strengths and weaknesses of the model that were identified. Limitations and opportunities with respect to model structure, complexity and uncertainty in parameter selection are then discussed. In addressing the second objective, challenges in applying the model to explore land management options and limitations for comparing outputs with natural resource targets are described. Finally, suggestions for model improvement are made and opportunities for future work are explored.

## 5.1. SWAT MODEL PERFORMANCE IN THIS STUDY

This study tested the ability of SWAT to simulate agricultural system processes such as vegetation growth, hydrology, erosion and herbicide transport in the Hodgson Creek catchment. Where measured data was not available, testing of model processes involved checking that the process simulated was logical. Where measurements were available, the model parameters were calibrated to provide a best fit of the model to observations, with the ability of the model to fit observed data taken as a measure of model performance. As data was available from paddock and catchment studies, the philosophy taken was to test and parameterise the model for HRU processes first (vegetation growth, hydrology and constituent generation), and then to test and calibrate the model against catchment data (hydrology and constituent delivery).

The processes were considered in order of process dependence. For HRU processes, the logic used was that plant growth creates biomass, part of which is transformed to residue and surface cover at harvest. Surface cover and plant growth modify potential evaporation and transpiration and hence soil water balance. Soil water in turn is used to modify the curve number, which controls the rainfall-runoff relationship, and erosion occurs on days of runoff only. Finally herbicide losses are controlled by the amount of herbicide in the soil surface, runoff and erosion rates. The model was tested in a logic order of crop yields, soilwater, runoff, erosion and herbicide loss. For catchment processes of routing and delivery, runoff was calibrated first, then sediment delivery and finally herbicide delivery.

### 5.1.1. Vegetation and soil water processes

Literature reviewed for this study showed few examples of where model vegetation dynamics had been tested. When it is considered that these processes provide fundamental building blocks of the bio-physical modelling approach, it was surprising that more authors have not investigated this area of the model. This study considered the processes of plant growth, surface cover and soil water in detail. These processes are underlying drivers of the bio-physical model method with soil cover and soil water important inputs into other HRU processes such as runoff and erosion.

Initial results from testing annual winter crops were promising. The model required minimal calibration to achieve good predictions of crop yields and surface cover. However, testing of summer cropping component revealed structural problems in SWAT associated with the end of a calendar year. This problem resulted in poor model performance and discontinuities in model outputs. There are fundamental problems associated with using the model with summer cropping scenarios in Australia. The affect that tillage has on residue cover in a sorghum farming system did not give satisfactory results and appears to be due to limitations in the ability of SWAT to model systems that pass over the end of a calendar year. This is one area that requires model improvement.

Testing also revealed that perennial pastures and trees are modelled similarly as annual crops. This results in perennial species showing seasonal fluctuations in biomass and leaf area index similar to annual crops. It may be possible to use SWAT for pastures if there is pasture dormancy during winter, but the model user would need to be aware that SWAT uses day length rather than temperature to initiate dormancy. This may result in reduced model performance. In this study modifications were made to the model code to the proportion of pasture biomass converted to dry stubble during dormancy to better reflect local knowledge of this process (the default of 95% was reduced to 70%). Modelling results for biomass dynamics of trees showed the model to be unrealistic. While the loss of leaf area may be suitable for deciduous species the associated loss of plant biomass is not. Watson *et al.* (2003) identified a similar issue when attempting to model Eucalyptus in southern Victoria. This study supports their conclusion that a better model for trees is required for Australian conditions.

#### 5.1.2. Runoff

Testing SWAT with paddock scale runoff data for winter crops and pasture provided results similar to those achieved by Littleboy *et al.* (1992a) with the PERFECT model. This provided confidence in the models ability to produce good predictions for runoff from HRU of cropping and pastures systems on a daily time step. Calibration against a range of tillage management practices showed that curve number reduced with tillage (Table 15), and provides a useful method of modelling the effect that management has on hydrologic processes.

When SWAT was subsequently tested at a whole of catchment scale, calibration provided curve numbers similar to those derived from calibration for a HRU. The ability to attain good predictions of monthly runoff is consistent with most other SWAT studies (Santhi *et al.*, 2001; Grizzetti *et al.*, 2003; Tripathi *et al.*, 2003; Watson *et al.*, 2003).

That curve number values for the whole of catchment calibration did not vary significantly from the HRU calibration suggests that the curve number method is scalable and supports the findings of Bingner (1997) and Chen and Mackay

(2004). This is an important finding and shows that hydrologic response of the model is not affected by the size of the HRU which suggests SWAT may provide a method to assess hydrologic change of catchment associated with land use change using small (1 ha) reference sites. On this basis, the curve number modelling approach could provide a method for water resource managers to improve understanding of how future land use or management scenarios may impact on water resource condition.

#### 5.1.3. Erosion and sediment yield

The erosion modelling component of SWAT was tested at the HRU scale using tillage management trial data. Results showed that long term erosion can be well represented using the USLE equations as implemented in SWAT (Table 16). USLE provides a long term average value but does not provide information on temporal variability in erosion. The assumption in this study is that good predictions using the USLE translate to good predictions using the MUSLE (this assumption is considered further in Section 5.2.1.). The MUSLE equations in SWAT determine daily sediment concentration from each HRU based on hillslope erosion rate, daily runoff and HRU area.

SWAT was also tested for its ability to estimate sediment delivery against observations from the Hodgson Creek sub-catchment (Figure 27). SWAT uses hydraulic equations to determine sediment transport capacity of a stream and consequently sediment yield. These hydraulic equations required input of stream channel characteristics such as dimensions, slope and roughness which were parameterised from field investigations. Manual adjustment of the peak flow rate adjustment factor was sufficient to match average annual sediment yield for the calibration period. However annual sediment loads variability was poorly matched.

It should be noted that the streamflow events used in this study for calibration of sediment yield were all reasonably small in comparison to historical flows. As such they may not be particularly representative of how the catchment responds in large events. While efforts were made to collect sediment yield data at a range of event scales, climatic conditions during the period of sampling limited the range of available data (see Figure 11).

It is also worth noting that measured data used for this study do not account for any bedload material. Merritt *et al.* (2003) point out that this lack of data is a particular deficiency in our knowledge base for river sediment transport. The delivery of eroded material can only be compared with the suspended sediment component, and material being transported as bedload is not considered.

#### 5.1.4. Herbicides

There are limitations in SWAT's ability to correctly simulate paddock scale processes. While observed data (Rattray *et al.*, 2007) shows a gradually decreasing concentration of herbicide with each runoff event through a season, when tested at a HRU scale SWAT indicates no herbicide losses after the first event. This suggests an exhaustion of the herbicide within soil layer considered as the herbicide mixing layer (top 1 cm of soil). This hypothesis remained untested as herbicide concentration in this mixing layer cannot be viewed as a SWAT output.

When SWAT predicted catchment scale yield of herbicide loads was tested against observed data (see Figure 28) the results were poor. This result was not surprising due to the poor performance at HRU scale. It was noted that changing the herbicide application date by a few days made the model response vary erratically.

Leonard and Wauchope in Knisel (1980) make the point that even under controlled conditions within field experiments estimating soil concentration of herbicide can be difficult due to the large number of factors controlling dissipation. At the catchment scale, additional uncertainties such as application dates, application rates and paddock condition at the time of application will all reduce the ability predict herbicide soil concentration and subsequently herbicide losses in runoff.

Herbicide application for summer cropping within Hodgson Creek is typically driven by the requirement for adequate rainfall to provide a planting opportunity. When this rainfall occurs, the result can be widespread residual herbicide application occurring across the catchment in narrow time frame. In the summer of 2000-2001 it was observed that sorghum planting and herbicide application occurred within a narrow time frame in early October across the catchment with a number subsequent runoff events in November and December. The observed data showed concentrations were highest at the start of the season and levels slowly reduced until late February. SWAT predicted loads two orders of magnitude higher than the observed data in the first event after application and then little thereafter. It is concluded that the for herbicide transport processes at the HRU scale in SWAT were inadequate and require substantial improvements before further testing of the model at a catchment scale are undertaken.

#### 5.1.5. Testing ability to represent management options of herbicides

It has been established that SWAT was not able to adequately represent herbicide observations at the HRU scale. However it was decided to explore the models capacity to apply the best management practices outlines in Table 4 in the modelling framework.

Reduction in application rate and testing of the effect of half life showed that SWAT was able to represent these processes well. However, there is hardly a need to set up a complex model to predict that reducing herbicide inputs by 50% had a similar affect on off site losses.

While SWAT provides detailed physical model processes for many of the major processes at work in catchments, HRU aggregation and lumping lets this process down. The example I give here is for the filter strips, for which a physical process of infiltration and sediment settling occurs in the model. However the process assumes unrealistic geometry of filters.

Filters strips reduced estimated herbicide loads substantially with a 20m filter reducing herbicide loads by 90% (Table 18). However application of this finding is limited by the way in which SWAT treats filters as edge of paddock filters and not as vegetated waterways as would be the case in this landscape. Figure 29 shows the SWAT representation of filter areas, where flow is considered to be a uniform sheet flow to the edge of a paddock and uniformly flows through a filter. However much of Hodgson Creek has contour banks which concentrate water to the edge of a paddock and into a waterways running downhill. This process misrepresentation means that the filter areas concept is unrealistic for local conditions. Given that this is the case then simply using a conceptual model (such as delivery ratio) would be easier to implement and provide more certainty of outcomes. This would require that future paddock scale research focus on deriving an understanding of what the delivery ratio for a range of filter types and widths should be.

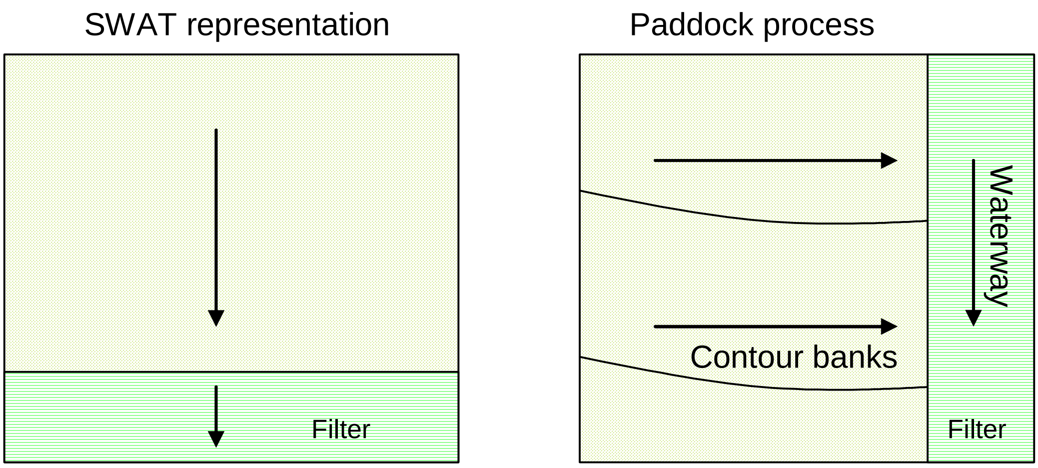



**Figure 29 : Process representation of edge of paddock filters where the arrows show direction of flow, the dotted area represents herbicide application area and the cross hatched area represents filter area.**

### 5.1.6. Summary of model performance

There were mixed results in the models ability to predict the effect of land management on hydrology and constituent generation. The model could represent the hydrology well across a range of scales (1-50,000 ha). It is also capable of predicting effect of tillage on runoff (daily) and erosion (average annual) at the HRU scale for winter cropping systems. However there are structural problem associated with the end of a calendar year which limits SWAT's ability to represent summer cropping systems. Limitations apply to the pasture and tree simulations by SWAT as they are modelled as modified annual crops, not true perennials.

At the catchment scale, monthly stream flow were acceptable, while annual sediment calibration was poor, and annual herbicides yield were poor. This is consistent with finding of Merritt *et al.* (2003) that uncertainty in hydrological modelling introduces an additional uncertainty into the sediment prediction and then further uncertainty again in a herbicide model. These results are important because paddock management has a moderate affect on runoff while it strongly influences erosion (Freebairn *et al.*, 1986). Paddock management is very important for herbicide loads and timing of application is extremely important for the transported concentration. It is therefore no surprise that as the spatial and temporal variability of catchment scale processes increase, so does SWAT's ability to adequately predict catchment scale responses.

## 5.2. MODEL STRUCTURE AND COMPLEXITY

### 5.2.1. Impact of disaggregation on sediment yield

An initial challenge in setting up SWAT was to identify the appropriate spatial resolution for sub-catchments and stream networks. Initial testing showed sediment yield predicted by SWAT was sensitive to the size of HRU used (not shown in this paper). Chen and Mackay (2004) found that sediment yield varied with the number and size of HRU due to the way in which the Modified Universal Soil Loss Equation (MUSLE) has been implemented in SWAT. The problem is that errors in sediment predictions are introduced through non-linearity of sediment yield by MUSLE. MUSLE defines a non-linear relationship between sediment generation and HRU area (see Equation 2.9), but sediment load is scaled linearly from HRU to catchment scale. Also, while land area surface connectivity is implicit in the MUSLE, SWAT aggregates HRU values without regard for this connectivity. These two problems result in HRU area effectively changing the model prediction considerably without another parameter or practice change occurring. Chen and Mackay (2004) present results showing 50% changes in catchment sediment yield caused simply by changing HRU areas.

For this study, the Hodgson Creek catchment was modelled as 4 major sub-catchments (see Figure 1). However it is apparent from the work of Chen and Mackay (2004) that if a different sub-catchment configuration had been adopted the sediment being generated at the HRU scale would have been different. This may have resulted in the calibrated peak rate adjustment factor (which controls sediment delivery in the stream channel) being different. This represents a limitation in being able to transfer parameters for sediment delivery to other catchments where HRU areas are different.

#### 5.2.2. Model complexity introduces error propagation

Uncertainty in model predictions is a function of an ability to characterise the catchment spatially, how well processes can be understood and an ability to validate model outcomes using observations of response characteristic we are concerned with (Grayson *et al.*, 1992). Uncertainty tends to increase as the number of processes that need to be predicted increases (Bevan, 1989).

This study used a method of calibrating model processes in order of process. An example is given from early model testing which describes the flow on affect that model complexity can have on error propagation.

In early testing of the model runs, it became apparent that at the start of simulation periods erosion behaved well, but after a few years erosion virtually stopped regardless of tillage practices. Model testing showed that soil cover (in the form of stubble) was not being degraded after a few seasons, with the result being that many tonnes of stubble were accumulating on the soil surface leading to very low erosion rate predictions. The reason for the stubble persistence was determined to be due to an algorithm limiting stubble degradation when nitrogen became limiting. It was also determined that the system was nitrogen deficient after 3 years. Initially the problem was resolved by using an automatic fertiliser application option in SWAT; an option whereby whenever nitrogen is limiting for any model process the model applies more to the system. Interestingly it was noted that a number of SWAT papers had stated that automatic fertilisation had been used. Using the automatic fertiliser option allowed modelling efforts to continue but still raised the question of why the system was running out of nitrogen. Searching for the major nitrogen consumption process in the system uncovered considerable denitrification, in excess of a 100 kg/ha/annum. Denitrification was being triggered when soil moisture reached 95 % of field capacity. Based on testing, the trigger point was eventually set at soil moisture of 105 % of field capacity, meaning that the soil had to be draining for denitrification to occur. This change reduced denitrification to <10 kg/ha/annum and resolved the original erosion dilemma. The process described above represents a case study for problems that highly complex models pose. Interacting processes can lead to this sort of knock on effect that can take considerable time and effort to uncover and raises the question about other processes that may be having an impact that is not as obviously apparent.

The problem outlined fits the concerns of Wooldridge *et al.* (2001) who report that the dominant paradigm in predictive catchment modelling for land use changes studies is a reductionist approach. A reductionist approach is defined by Wooldridge *et al.* (2001) as detailed studies of individual disciplines lumped together to create a model framework. The example given above fits this paradigm and shows the impact that model complexity can have through error propagation. Wooldridge *et al.* (2001) also argue that this modelling approach suffers from problems such as; small scale derived properties may not necessarily be applicable at larger scales, integrating these processes requires more information about the heterogeneity of the application area than it is possible to obtain, and measurements (and hence derived parameters) may well be event specific. They also argue that the models developed through a reductionist approach are typically highly over parameterised and ill posed with respect to data. This can result in parameter combinations which adequately predict the observed catchment response, but have low predictive capacity in independent data sets.

## 5.3. APPLYING SWAT IN WATER QUALITY ASSESSMENT

In this section the challenges and limitations found in the ability of SWAT to model land management impacts on water quality are discussed. Many of these limitations are associated with the limited information on spatial and temporal distribution of farm management practices.

### 5.3.1. Managing model inputs and outputs

SWAT is a highly complex model. Merritt el al (2003) argue that this type of complexity inherent in physically based models results in a requirement to handle large amount of input and output data and consequently they can be difficult to use. I found this to be true of SWAT. There are literally hundreds of coded routines and processes, and many thousands of parameters to deal with in the model. In addition, values for models parameters can vary temporally or spatially. The vast majority of parameters however are not locally quantifiable due to a lack of observations of the particular process and it is expected that modellers will use the default parameters. It is uncertain whether default parameters adopted in this study are suitable for the local conditions.

During the process of setting up the SWAT model for the whole of catchment analysis over 400 input files were generated. Each of these files contains many dozens of parameters. Practically, it is simply not possible to check that all of the parameters are suitable or that no errors exist in input data. Equally challenging is the many hundreds of output parameters from the model, most of which are daily time series. The objective of the study was aimed at more than simply assessing whether long term average outcomes could be achieved, but to check that important processes for were being carried out realistically. As the SWAT interface did not easily allow time series outputs from the model to be viewed and the logistics of cutting and pasting large data sets into spreadsheets was not an attractive option, an alternative was sought. This alternative was found in the Browser software described in Section 3.3.3. It was only when it was possible to see model predictions of such things as plant growth that it was apparent that improvements were needed in various component of the model.

While the Browser software allowed for new insights into the dynamics of time series outputs, a further challenge was that some modelled processes of interest to this study were not outputted. For example, an important model process not outputted was the surface residue cover. As this is a major driver of erosion (Freebairn and Wockner, 1986) and hence the models ability to predict management outcomes due to tillage, not being able to see this output severely limited confidence in the model. By changing model code to output those processes and interrogating the model processes it was possible to test SWAT's ability to model land management effects.

#### 5.3.2. Defining the spatial extent and variation in soils

There is some uncertainty regarding the spatial extent of mapped soils used in this study. In deriving data for this study it was necessary to ask a soil scientist (Biggs) to consolidate soils maps to a manageable number of soils groups. While every care was taken during this process, it still results in soil groups that are not in reality homogenous as the model portrays them.

Each soil group may represent a particular texture of soil that varies in depth. The soil is then represented in the model with the average depth over the grouped area. Part of the reason for this process of grouping was due to limited observations of physical characteristics. A useful data set would be one that characterises a distribution of parameters for soils. However, typically only one or two field observations are available for a soil that is then applied as the value for many thousands of hectares. This is not an area of uncertainty which can easily be addressed due to resource constraints.

#### 5.3.3. Defining the temporal variation of land management practices

Through the process of this study a number of data sets were sourced to determine current land use and management. Land use was defined in the study area using aerial photo interpretation. Land management for the study area was broadly defined based on discussion with local farming and agronomic expertise. This information provided an estimate of adoption rates of various tillage practices and rules on herbicide management.

A challenge to applying SWAT is uncertainty associated with specifying field practices for Australian conditions. SWAT requires the user to input crop practices as a fixed rotation, whereas in reality Australia's highly variable climate with unreliable seasonal weather patterns have resulted in opportunistic farming practices, that is crop selections and associated management actions are reactive to short term climatic variation.

Locally developed models, such as PERFECT (Littleboy *et al.*, 1992a), provide for this by having planting and tillage rules that rely on climatic conditions being met to trigger a management action. By way of example, the user specifies a planting period (a window of opportunity), a minimum amount of soil water (as a percentage of the total at field capacity) and an amount of rainfall that must fall in a set period (i.e. 25 mm in 7 days), and only when all of these conditions are met will the model plant a crop. As SWAT does not permit these ruled based management options the possibility for unrealistic scenarios to be modelled arises, such as crops being planted in dry periods when most farmers would not actually plant crops.

Erosion will also be sensitive to operations timing and may partly account for the errors that were observed in predicting catchment scale sediment yield. Modelled tillage events that do not coincide with actual tillage in a catchment would lead to errors in residue cover level predictions and hence subsequent errors in erosion. This study showed the importance of tillage practice on erosion (Table 16) with an order of magnitude difference in erosion rates between some practices. This highlights the importance of getting the spatial and temporal variation in practices correct in being able to validate the catchment model against end of catchment observations.

This same logic applies to herbicide management options, as one of the major drivers for herbicide application is rainfall. A small rainfall event (<20 mm) may cause weeds to germinate but not be sufficient to plant crops on, meaning that herbicides might be used in a fallow situation, leading to a window of risk of off site movement. Capturing this type of behaviour is important as it would better captures real drivers of management leading to the off site risk, and would be an improvement over the fixed system currently employed in SWAT. However for this study we simply had little information on the timing of the herbicide application in this catchment. While generalised information on usage patterns of herbicides was collected, specific details on a farm by farm basis was not available.

This leads me to believe that while we have a model able to deal effectively with farm operation; in attempting to validate the model at a catchment scale we have little certainty about the types of operations to apply and where to apply them. Hence this is a major limitation in the models ability to predict catchment outcomes, particularly for erosion and herbicide losses which are highly dependant on farming operation timing.

#### 5.3.4. Limitations for comparing model outputs with natural resource targets

When reviewing the literature it was assumed that SWAT would provide a suitable tool for modelling herbicide transport at the catchment scale. Water quality triggers use daily concentrations (NHMRC, 2004; ANZECC, 2000) and Neitsch *et al.* (2002) provided an example of validating SWAT against daily herbicide concentrations. However, this report on the use of SWAT to provide daily herbicide concentrations is misleading as the model output is given in daily loads. While it may have been possible to re-compile the model to output concentrations rather than loads this would have been a considerable undertaking primarily due the model structural. Given the poor performance of SWAT at modelling herbicides which were identified during the HRU validation process, pursuing this option was not considered feasible.

The limitation of having a model that provides load estimates potentially limits the capacity of SWAT to be used in setting natural resource targets. Even if the model was able to adequately represent the processes and a model user was able to adequately parameterise the model to provide good load estimate, this may still be insufficient to answer questions relating to natural resource outcomes. The trigger values provide an indication of ecological and human health impacts that herbicides have based on studies utilising concentrations not loads. It is therefore reasonable to expect that target setting would also be based on daily concentrations of herbicides which SWAT is not currently able to model.

## 5.4. MODEL IMPROVEMENTS AND FUTURE WORK

### 5.4.1. Model processes that require improvement

This study has investigated many of the components of SWAT considered important to being able to model herbicide movement at a whole of catchment scale. Through the course of this work a number of aspects of the model were identified that require improvement. However there are many aspects of SWAT not investigated in this study that may also require improvement.

Of most paramount importance is that the herbicide model in SWAT needs revision and improvement. This study established that the model was not able to reproduce the sort of behaviour expected when compared to paddock scale herbicide loss trials. As part of the revision it would also be an advantage to have the model output herbicide soil concentrations and daily concentrations at the HRU scale. Outputting these variables would allow the model to be adequately tested against paddock scale trial data.

There is also an obvious need to improve the manner in which the summer annual and perennial crops are being modelled in SWAT. The current implementation limits the usefulness of SWAT for investigating the impacts that these land uses and the effect of land management for Australian conditions. It was determined that a number of the model limitations are due to a structural problem associated with the end of a calendar year in SWAT.

As identified in section 6.3.3, locally developed models, such as PERFECT (Littleboy *et al.*, 1992a), use a rules based approach to trigger a management action (i.e. crop planting, tillage) and the argument for this approach to be adopted in SWAT is not repeated here. However, one of the main innovations with the method employed in PERFECT (Littleboy *et al.*, 1992a) was to dynamically modify curve number with surface cover. This lets the curve number automatically adjust to account for surface cover (and hence tillage) and has been shown to improve the capacity to model surface runoff using the SCS curve number approach (Owens *et al.*, 2003). During the development of CREAMS, Knisel (1980) concluded that there was not enough evidence to support modifying curve numbers dynamically with cover and this conclusion has flowed onto SWAT. However it is likely that dynamic modification of the curve number would improve the model for application in Australian conditions where annual variability in surface cover can be large.

### 5.4.2. Future work

It was found in this study that the curve number method is scalable, and that SWAT could provide a method for water resource managers to improve understanding of how future land use or management scenarios may impact on water resource condition. Future studies may be able to utilise this finding to study the impact that changes in land use (e.g. cropping to pastures) or the widespread adoption of conservation tillage practices may have on downstream water resource quantities.

It was suggested at the outset of this study that a catchment model was needed to set realistic targets for suspended sediment and herbicides based on the adoption of agricultural BMP. This study has concluded that SWAT is not currently able to fulfil that role. This means that further research is needed into finding a suitable model is required. While many of the problems identified in SWAT may be able to be improved upon (as suggested in section 6.4.1), the issue still remains that SWAT is overly complex. I believe that a simpler conceptual model that does not suffer the problems of model complexity, and resultant uncertainty identified with SWAT is called for. An example of a possible method is given by Rattray *et al.* (2005) where the paddock scale bio-physical modelling approach has been integrated to a catchment scale using a conceptual model of delivery.

Regardless of the tool or method of catchment modelling used, it is apparent that research and development of methods to better understand the spatial and temporal variation in paddock scale practices are required. This will allow improved parameterisation of models and hopefully improve the capacity to validate models against catchment outlet observations. This will then establish a credible basis for scenarios testing of a model to integrate practice change at paddock scale to whole of catchment water quality outcomes.

# CHAPTER 6. CONCLUSION

The aim of this study was to determine if a model could be used to calculate effects of farming practices at a paddock scale on transport of herbicides at a catchment scale. The study aimed to establish the feasibility of using the SWAT model to explicitly depict farm management practices at a paddock scale to estimate resultant catchment water quality outcomes. Results of model testing were mixed for processes such as vegetation growth, hydrology and erosion, and were poor for herbicide processes. Across all model processes tested the reason for poor model performance can be attributed to both inadequate representation of the processes at HRU scale and difficulties in parameterisation of spatial and temporal inputs at catchment scale.

Data available for model testing came from both paddock and catchment studies. The philosophy taken was to test and calibrate the model for HRU processes first (vegetation growth, hydrology and constituent generation), and then to test and calibrate the model against catchment data (hydrology and constituent delivery).

Literature reviewed for this study showed few examples of where model vegetation dynamics had been tested. When it is considered that these processes provide fundamental building blocks of the bio-physical modelling approach, it is surprising that more authors have not investigated this area of the model.

Initial results from testing annual winter crops were promising. The model required minimal calibration to achieve good predictions of crop yields and surface cover from these crops. However, testing of summer cropping component revealed structural problems in SWAT associated with the end of a calendar year. This problem resulted in poor model performance and discontinuities in model outputs. Testing also revealed that perennial pastures and trees are modelled as if they are annual crops. This results in perennial species showing seasonal fluctuations in biomass and leaf area index similar to the annual crops that were unrealistic.

The model was able to represent hydrology well across a range of scales (1-50,000 ha). The ability to attain good predictions of monthly runoff at the catchment scale is consistent with most other SWAT studies.

The model was able to good representation of average annual erosion using the USLE when tested at the HRU scale against a range of tillage management data. As the USLE is not intended to predict the temporal variability in erosion, SWAT uses the MUSLE to determine the daily sediment generation rates from HRU. The MUSLE uses the amount of daily runoff and peak runoff rate to simulate daily erosion and sediment yield. Initial testing showed sediment yield predicted by SWAT was sensitive to the size of HRU used due to the way in which the MUSLE defines a non-linear relationship between sediment generation and the HRU area. SWAT integrates sediment yield from a HRU and uses a streampower method to deliver sediment to a catchment outlet. Model calibration, using a peak flow rate adjustment factor, resulted in average annual sediment yield for the period of calibration to be matched; however variability in annual sediment loads was poorly matched.

Testing of the herbicide model for SWAT revealed that modelled process compared poorly with paddock scale trial data. SWAT predicted off site losses of herbicides for the first runoff event after herbicide application, but then no more thereafter, while paddock scale trial data showed significant losses of herbicide in the first four runoff event after application. When catchment scale yield of the herbicides predicted by SWAT were compared with observed data the results were poor. It was noted that changing the date of application resulted in the modelled annual load responding erratically.

While SWAT provides detailed physical sub-models for major processes effecting land use, hydrology, erosion and herbicide transport, the capacity to parameterise each of the sub-models both spatially and temporally is limited. Particularly challenging is uncertainty associated with specifying field practices for Australian conditions. SWAT requires a user to input crop practices as a fixed rotation while the reality for Australia's highly variable climate is opportunistic farming practices. This appears to be a major limitation in the models ability to predict catchment outcomes, particularly for herbicides where off site losses are highly dependant on application timing. In attempting to validate herbicide losses at the whole of catchment scale it became apparent that uncertainty in temporal variation of farm operations within a catchment poses a major limitation to accurately reproducing observations at a catchment outlet.

While every effort was made during this study to validate processes considered important to the models performance in this application, a major cause of uncertainty in SWAT is that there are many processes being modelled which have little or no means of validation. This leaves literally hundreds of parameters and dozens of processes that have gone unchecked and unaccounted for in their potential to introduce further model uncertainty.

The concept of using a bio-physical model for catchment scale water quality assessment appeared attractive at the outset of the study. It was envisaged that such a model would allow the affect of farm management practices to be integrated such that whole of catchment water quality assessment could be made. However problems associated with the mis-representation of key processes in SWAT and a limited ability to define where and when farm practices occur in the catchment resulted in poor model validation results. It is concluded that there is limited usefulness of SWAT for investigating the impacts of land management on catchment scale herbicide transport for Australian conditions.

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## APPENDIX A : MAPS

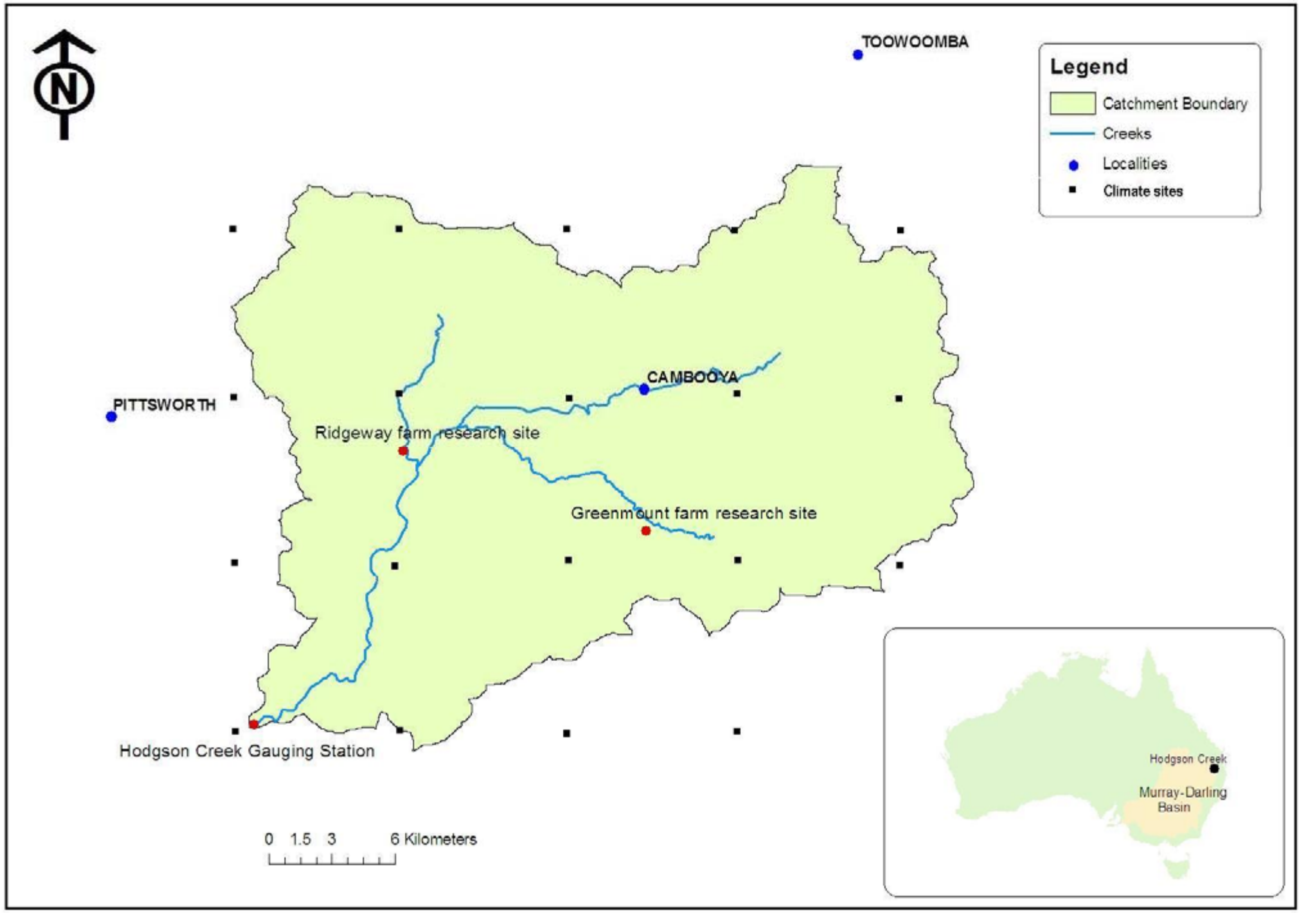
Map 1 : Locality map of area showing location of gauging station, paddock scale research sites and climate stations.

Map 2 : Digital elevation model.

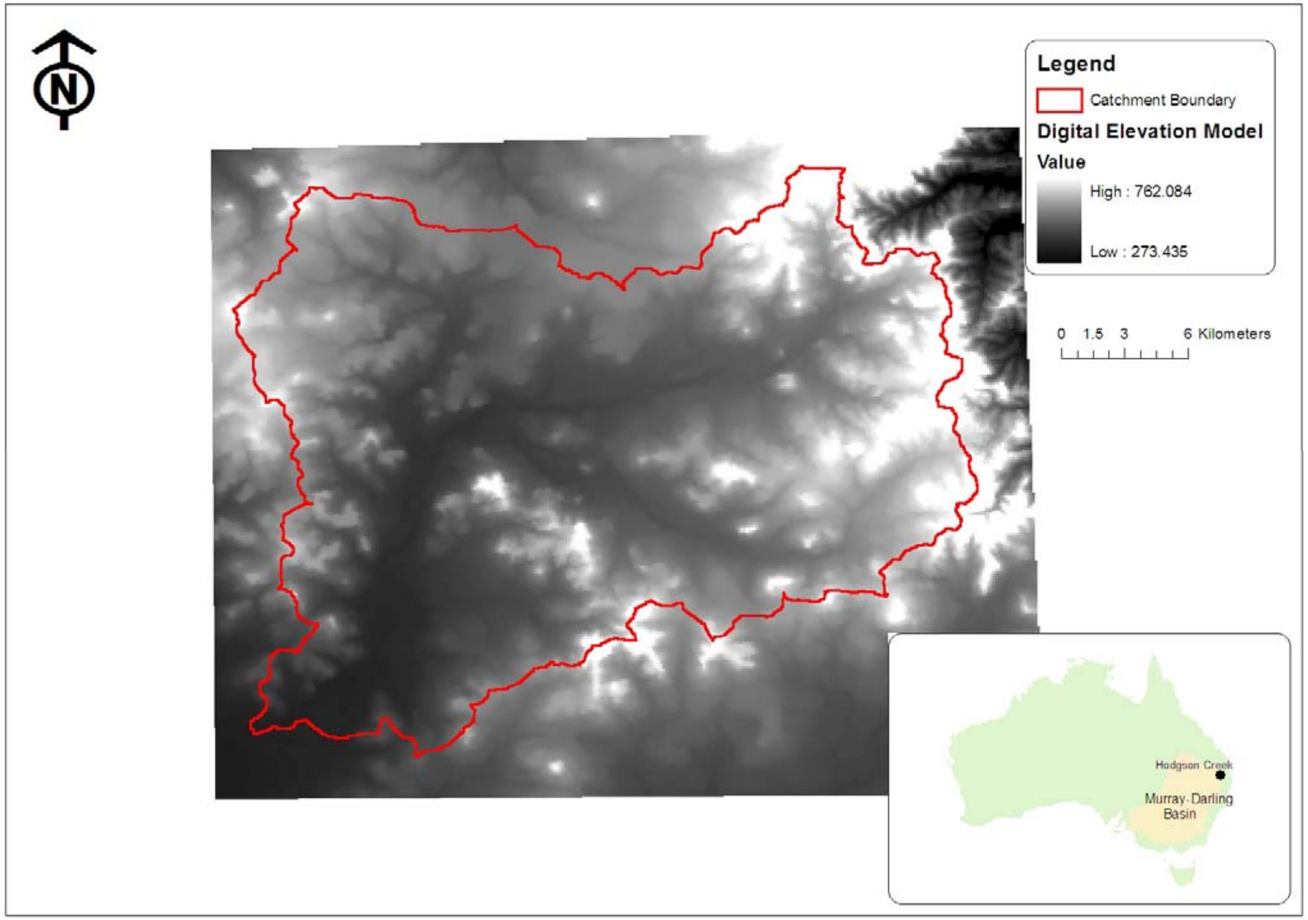
Map 3 : Detailed soils map

Map 4 : Simplified soils map

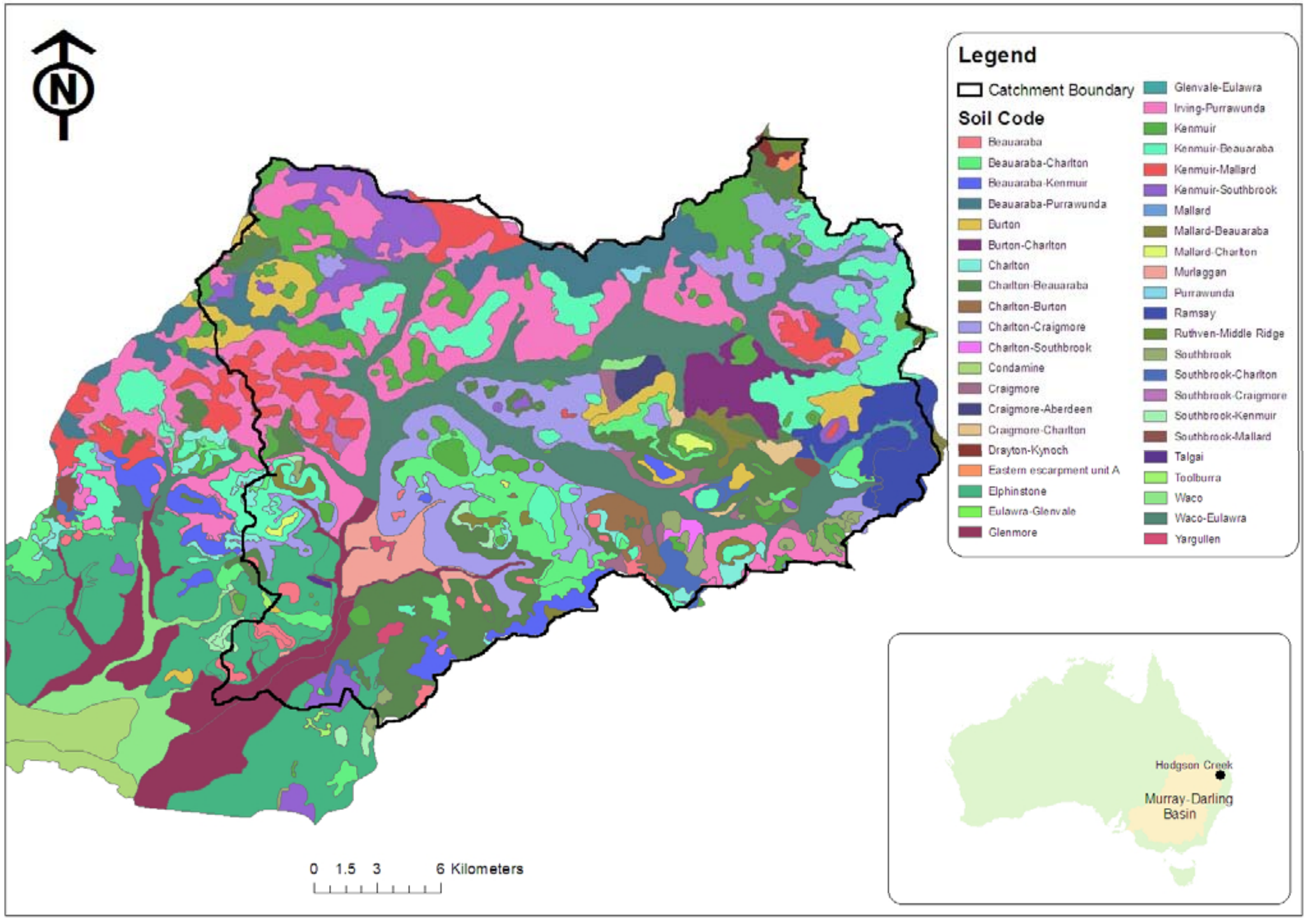
Map 5 : Land use map



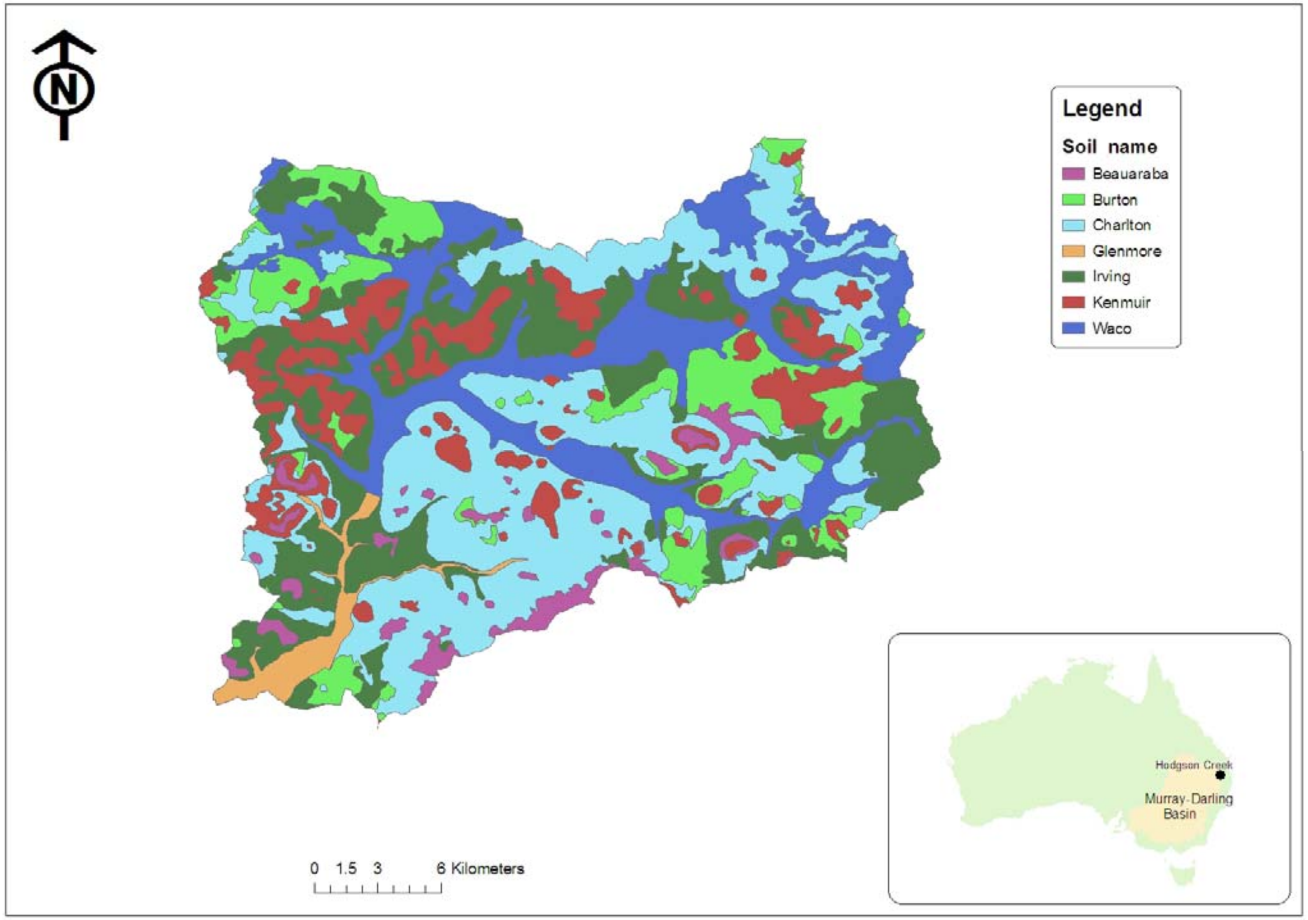

**MAP 1 : LOCALITY MAP SHOWING GAUGING STATION, RESEARCH SITES AND CLIMATE STATIONS.**



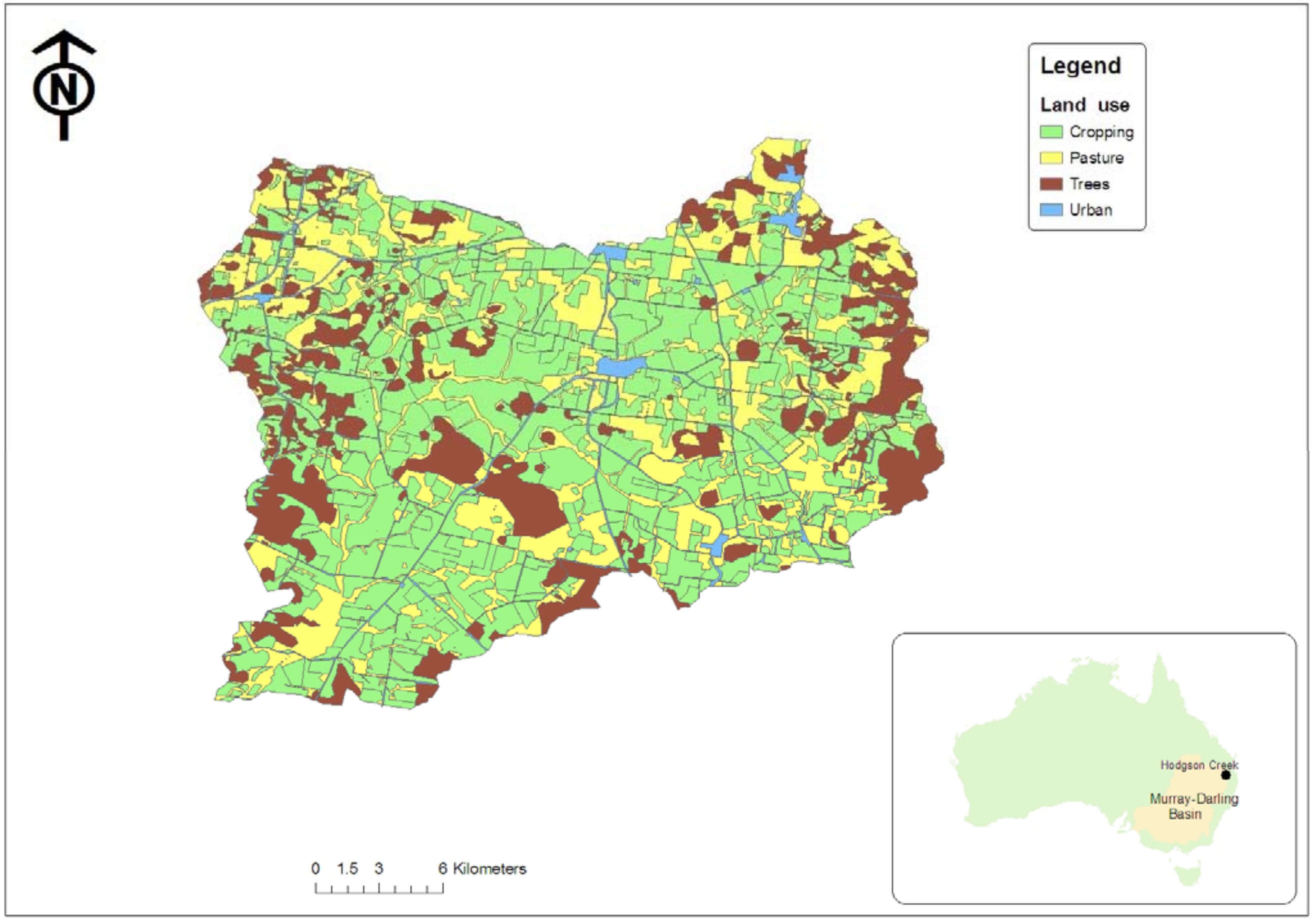

**MAP 2 : DIGITAL ELEVATION MODEL (DEM).**




**MAP 3 : DETAILED SOILS MAP.**




**MAP 4 : SIMPLIFIED SOILS MAP.**




**MAP 5 : LAND USE MAP**

# APPENDIX B : –FORTRAN SOURCE CODE CHANGES

File: D:\SWAT\code\SWAT2000\swat_dr_05\Code changes\Code changes.TXT 13/01/2005, 9:52:34AM

```
 These changes were made for the SWAT_dr_05.exe  1/05


 dormant.f

 DJR - This changes the means that 70% of biomass gets converted to residue
at dormancy - up from 5%
 DJR - second changs are to stop wheat going dormant during winter
 !! beginning of perennial (pasture/alfalfa) dormant period
          case (3, 6)
            idorm(j) = 1
            resnew = 0.
            resnew = .7  * bio_ms(j)                    !!changes from
resnew = 0.05 *bio_ms(j)  DJR 4/04
            sol_rsd(1,j) = sol_rsd(1,j) + resnew
            sol_rsd(1,j) = Max(sol_rsd(1,j),0.)
            sol_fon(1,j) = sol_fon(1,j) + snup(j)
            sol_fop(1,j) = sol_fop(1,j) + spup(j)
            dm2(nro(j),icr(j),j) = bio_ms(j) + dm2(nro(j),icr(j),j)
            dmanu(j) = dmanu(j) + bio_ms(j) / 1000.
            bio_ms(j) = .3  * bio_ms(j)                 !! changed from
bio_ms(j) = .95  * bio_ms(j)  DJR 4/04
            snup(j) = 0.
            spup(j) = 0.
            strsw(j) = 1.
            alai(j) = alaimin
            phuacc(j) = 0.


          !! beginning of cool season annual dormant period
        ! case (2, 5)                           !DJR removed start dormant
for cold annuals
        !   if (phuacc(j) < 0.75) then
        !     idorm(j) = 1
        !     strsw(j) = 1.
        !   end if

  nminrl.f

  DJR - This change means that soil water needs to be 1.05 * field capacity
for denitrification to occur - up from 0.95

      real, parameter :: cdn = -1.4, sdnco = 1.05        !! changed from
real, parameter :: cdn = -1.4, sdnco = 0.95   DJR 1/05
      integer :: j, k, kk
      real :: rmnl, rmp, xx, csf, rwn, hmn, hmp, r4, cnr, cnrf, cpr
      real :: cprf, ca, decr, rdc, wdn, cdg, sut

!! compute denitrification
          wdn = 0.
          if (sut >= sdnco) then
            wdn = sol_no3(k,j) * (1. - Exp(cdn * cdg * sol_cbn(k,j)))


  sbsday.f
  DJR - To better understand model processes soem addional parameters were
outputted

      pdvas(53) = bio_ms(j)*(1-rwt(j))   ! DJR & JYY aug 2004
      pdvas(54) = bio_ms(j)              ! DJR & JYY aug 2004
```

```
      pdvas(55) = alai(j)                  ! DJR & JYY aug 2004
      pdvas(56) = 0.0                       !!yield only defined at annual
and average annual
      pdvas(57) = bio_ms(j)*rwt(j)          ! DJR & JYY aug 2004
      pdvas(58) = rwt(j)                    ! DJR & JYY aug 2004
      pdvas(59) = sol_cov(j)               !this CV in Eqn 2.2.16     JYY and
DJR - added residue output
      pdvas(60) = sol_rsd(1,j)              ! this is rsdsurfi -  in JYY and
DJR - added residue output

reachout.f
DJR - to better understand pesticide processes addtional parameter were
outputted to reach file

      rchdy(40,jrch) = varoute(20,ihout)                    !!!solpst out
(mg/m^3 pst)   !!!DJR 8/7/03
      rchdy(41,jrch) = varoute(21,ihout)                    !!!!srb out
(mg/m^3 pst)   !!!DJR 8/7/03
      rchdy(42,jrch) = varoute(22,ihout)                    !!!!totpst out
(mg/m^3 pst)   !!!DJR 8/7/03

rchday.f
DJR - again some changes needed to read out rch pesticide parameters
        pdvar(40) = rchdy(40,j)     !!solpst out (mg/m^3 pst)   !!!DJR
8/7/03
        pdvar(41) = rchdy(41,j)     !!!srb out (mg/m^3 pst)   !!!DJR 8/7/03
        pdvar(42) = rchdy(42,j)     !!!totpst out (mg/m^3 pst)   !!!DJR
8/7/03


header.f
DJR - these changes to header as to match sbs and rch  from above
     &         "agBIOkg/ha","  BIOkg/ha","       LAI","   YLDt/ha",     &
!JYY and DJR - changes BIOM units to kg/ha
     &         "bgBIOkg/ha","       rwt","slcovkg/ha","sol_rsdly1",     &
!JYY and DJR

          &         "SOLPSTmg/m^3","SORPSTmg/m^3","TOTPSTmg/m^3"/)
!DJR 1/05


            -----------------PEST CHANGES--------------
In addition to the changes shown above the model used for PEST had full
precision on the  output files
Full precision was needed on the .sbs output file and the .swt output file
(ie saveconc)

OPENFILE.f
            open (1,file=rsvout,recl=600)
cjd      open (3,file=sbsout,recl=800)            !jd
      open (3,file=sbsout,recl=1000)            !jd



saveconc.f
                  return
 2000 format (1x,i4,2x,i3,1x,i2,14(1x,e14.7))     !DJR 1/05
 1000 format (1x,i4,2x,i3,3x,14(1x,e14.7))        !DJR 1/05
      end
```

sbsday.f

```
      return
cjd 1000 format (a4,i4,1x,i8,1x,i4,1x,i4,1x,i4,e10.5,65f10.3)  !jd
 1000 format (a4,i4,1x,i8,1x,i4,1x,i4,1x,i4,e14.7,1x,65(e14.7,1x))    !jd
      end
```