HowLeaky Model V5
Technical Documentation

Version 1.09

Queensland
Government

Prepared by: David McClymont, DHM Environmental Software Engineering Pty Ltd. This document is a joint publication between the Department of Natural Resources, Mines and Energy and the Department of Environment and Science.

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About this Document

HowLeaky is a software model that has been designed to assess the impacts of different land uses, soil conditions, management practices and climate-types on water balance and water quality. It can provide reliable and flexible results from limited input data for a wide range of land use studies. It is highly suited for benchmarking and comparison of land use practices and exploring and highlighting the impacts of changing key variables on the system response. ***HowLeaky*** is particularly useful for investigating the water quality and erosion effects of agricultural practices such as irrigation, tillage, pesticide and nutrient (N and P) applications.

This document aims to provide ***HowLeaky*** users and developers with a detailed scientific description of the simulation model contained within the ***HowLeaky*** software (Version 5.49). This includes documentation of the scientific model equations, algorithms and descriptions of the input and output parameters. Sample input parameter values for different submodels are provided in the appendices. This document does not aim to provide any information about the running of the software nor the features of its user-interface.

This document represents a compilation of writings extracted from technical reports, journal articles, notes and computer code from the last 30 years. A large component of this text has been adapted from the ***PERFECT*** V3 Manual (Littleboy, Freebairn, Silburn, Woodruff & Hammer, 1999), which describes the underlying model from which ***HowLeaky*** is derived. Authorship is often blurred with a large number of contributors over the period of the model's genesis from ***PERFECT*** through to the current version. Development of the model has often been ad-hoc and unstructured, with gaps in the documentation during some years of development. This is reflected in this document with some sections being more detailed than others, with different documentation styles and notation used.

We would like to acknowledge the contributions from many individuals for inputs into the ***HowLeaky*** development. This includes the original ***HowLeaky*** development team of David Freebairn, David McClymont, Brett Robinson, Dan Rattray, Mark Silburn and Melanie Shaw, and the original ***PERFECT*** authors including Mark Littleboy, David Freebairn, Mark Silburn, David Woodruff and Graeme Hammer. Other significant contributions were provided by (in alphabetical order) Chris Carroll, Lex Cogle, Ted Gardner, Thabo Kumaran, Paul Lawrence, Jyoteshna Owens, Anna Roberts, Kerry Rosenthal, Mark Sallaway, Craig Thornton and Don Yule.

Contents

1. Introduction

1.1 About the *HowLeaky* model

The "***HowLeaky*** [1] model" is a daily time-step water balance model that derives from and extends the ***PERFECT*** V3 model (Littleboy, Freebairn, Silburn, Woodruff & Hammer, 1999). ***HowLeaky*** has been designed to assess the impacts of different land uses, soil conditions, management practices and climate-types on water balance and water quality. It can provide reliable and flexible results from limited input data for a wide range of land use studies. It is highly suited for benchmarking and comparison of land use practices and exploring and highlighting the impacts of changing key variables on the system response. It is particularly useful for investigating the effects of agricultural practices associated with cropping such as irrigation, tillage, pesticide and nutrient (N and P) applications.

PERFECT and ***HowLeaky*** have been extensively validated with hydrology data for cropping systems in Queensland for runoff, erosion and the movement of nutrients attached to sediments (for example, Littleboy, Silburn, Freebairn, Woodruff, Hammer & Leslie, 1992a; Littleboy, Freebairn, Hammer & Silburn, 1992b; Chamberlain, Silburn & Owens, 2009; Freebairn, SIlburn & Lock, 2009). In addition, the ***HowLeaky*** pesticide and phosphorus submodels have been validated by Shaw, Silburn, Thornton, Robinson and McClymont (2011), Robinson, Shaw, Silburn, Roberts, Vigiak and McClumont (2011) and Anzooman, Silburn, Waters, and Craig (2013), and are currently being used in Queensland Government's Reef Plan program (http://www.reefplan.qld.gov.au).

1.2 Genesis of the *HowLeaky* and *PERFECT software packages*

The need to assemble a multi-disciplinary group to study cereal cropping systems through the application of simulation models was identified by Queensland Department of Primary Industries (QDPI) in 1980 resulting in the development of ***PERFECT***. The objective of this multi-disciplinary group was to develop and validate models of erosion and productivity to study production and degradation aspects of cereal cropping systems. A major benefit of this group was the convergence of crop models developed and validated by the QDPI Agriculture Branch and the water balance and erosion models developed and validated by the QDPI Soil Conservation Research Branch. Initially, an existing model for wheat growth (later described in Hammer, Woodruff & Robinson, 1987) was integrated with a range of water balance and erosion sub models. This stage of the development of ***PERFECT*** was described by Freebairn, Silburn, Hammer & Woodruff (1986). The development of ***PERFECT*** was finalised from 1986 to 1989 (Littleboy, Silburn, Freebairn, Woodruff & Hammer, 1989). During these years, ***PERFECT*** became a cropping systems model with a substantial number of new components including crop growth submodels for sunflower and sorghum, crop residue and surface cover submodels, a wider range of erosion submodels (to model the effects of erosion on productivity), an in-crop nutrient balance submodel, and planting and tillage decision submodels. ***PERFECT*** was developed to simulate the major effects of management (cropping system and tillage) and environment (climate and soil type) and to predict runoff, soil loss, soil water, drainage, crop growth and yield. The development of ***PERFECT*** involved:

- incorporating crop growth submodels for wheat and sunflower into ***PERFECT***;
- including hydrology and erosion relationships developed from experimental data collected from small agricultural catchments and rainfall simulators in Queensland;

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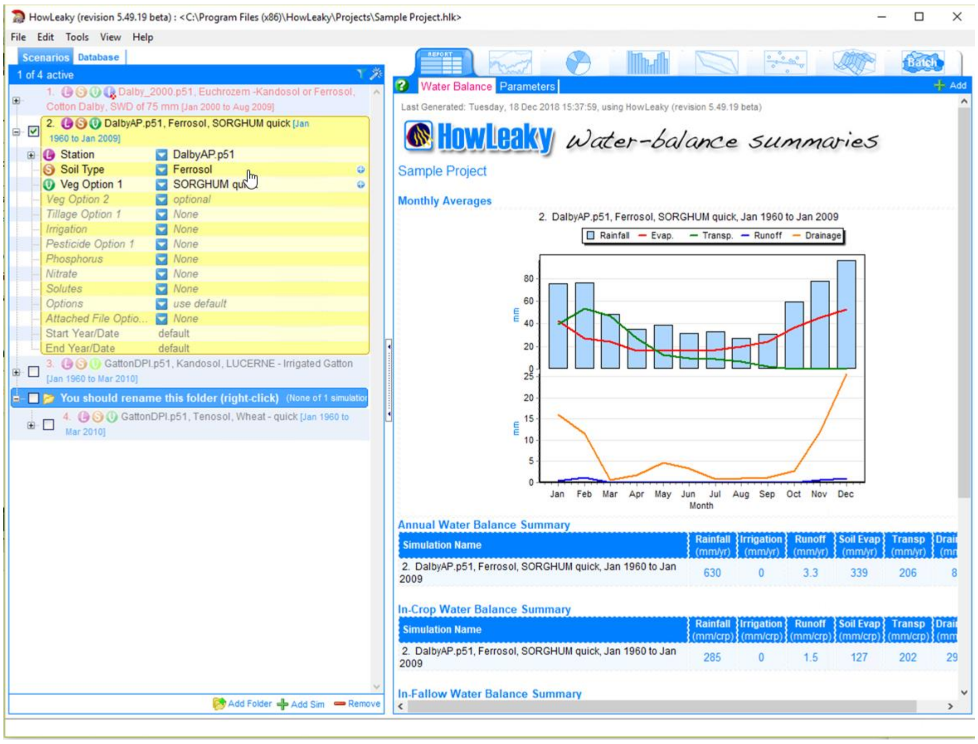
[1] While the term "***HowLeaky***" can be used interchangably to denote either the "software" or the "model", we will refer to the scientific model as the "***HowLeaky*** model" and the software as the "***HowLeaky*** software".

- adapting components from published models such as CREAMS (Kinsel, 1980; Rawls, Onstad & Richardson, 1980) and EPIC (Williams, 1983);
- including planting and tillage submodels to determine the timing of planting and tillage operations as a function of rainfall, time of year and soil moisture; and
- integrating these components into a framework that simulates both crop and fallow phases of a cropping system.

This model was used in both Australian and India. In Australia, ***PERFECT*** was applied in numerous projects funded by the National Landcare Program, Land and Water Resources Research and Development Corporation (LWRRDC), Australian Centre for International Agricultural Research, and the Murray-Darling Basin Commission. K.P.C. Rao and S.T. Srinivasan from the International Crops Research Institute for the Semi-Arid Tropics (Hyderabad, India) were involved in the adaption of ***PERFECT*** for Indian farming systems.

PERFECT was initially funded by the Queensland Department of Primary Industries Director-General New Initiatives scheme from 1983 to 1986. From 1987 to 1989 the National Soil Conservation Program provided substantial funding to finalise development and the subsequent documentation of ***PERFECT***. From 1990 until 1992, the LWRRDC provided funding for ongoing model validation. Since 1992, maintenance and development of ***PERFECT*** has continued largely due to the support and sustenance from the Queensland Department of Natural Resources (now Department of Natural Resources, Mines and Energy).

In 2000, the first version of ***HowLeaky*** software was developed for the Microsoft Windows operating system which took the ***PERFECT*** V3 science code and encapsulated it within a powerful and flexible C++ based graphical user interface (**Figure 1**). It extended the ***PERFECT*** model through numerous subtle refinements of the core model and a range of new submodels simulating different management practices for irrigation, pesticide, phosphorus, nitrate and solutes. ***HowLeaky*** could run simulations in under one second (compared to 10-20 seconds for latest versions of ***PERFECT***) and users could plot and rapidly interact with over 100 time-series outputs. This development progressed rapidly over the next 10 years aided by continual advances in the graphical user interface which empowered modellers to better visualise model inputs, outputs and system interactions.



HowLeaky (revision 5.49.19 beta) : <C:\Program Files (x86)\HowLeaky\Projects\Sample Project.hlk>

1 of 4 active

1. Dalby_2000.p51, Euchrozem -Kandosol or Ferrosol, Cotton Dalby, SWD of 75 mm [Jan 2000 to Aug 2009]

☑ 2. DalbyAP.p51, Ferrosol, SORGHUM quick [Jan 1960 to Jan 2009]

Station	DalbyAP.p51
Soil Type	Ferrosol
Veg Option 1	SORGHUM qu
Veg Option 2	optional
Tillage Option 1	None
Irrigation	None
Pesticide Option 1	None
Phosphorus	None
Nitrate	None
Solutes	None
Options	use default
Attached File Optio...	None
Start Year/Date	default
End Year/Date	default

☐ 3. GattonDPI.p51, Kandosol, LUCERNE - Irrigated Gatton [Jan 1960 to Mar 2010]

☐ You should rename this folder (right-click) (None of 1 simulatio

☐ 4. GattonDPI.p51, Tenosol, Wheat - quick [Jan 1960 to Mar 2010]

Last Generated: Tuesday, 18 Dec 2018 15:37:59, using HowLeaky (revision 5.49.19 beta)

HowLeaky Water-balance summaries

Sample Project

Monthly Averages

2. DalbyAP.p51, Ferrosol, SORGHUM quick, Jan 1960 to Jan 2009

Annual Water Balance Summary

Simulation Name	Rainfall (mm/yr)	Irrigation (mm/yr)	Runoff (mm/yr)	Soil Evap (mm/yr)	Transp (mm/yr)	Drai (mn
2. DalbyAP.p51, Ferrosol, SORGHUM quick, Jan 1960 to Jan 2009	630	0	3.3	339	206	8

In-Crop Water Balance Summary

Simulation Name	Rainfall (mm/crp)	Irrigation (mm/crp)	Runoff (mm/crp)	Soil Evap (mm/crp)	Transp (mm/crp)	Drai (mm
2. DalbyAP.p51, Ferrosol, SORGHUM quick, Jan 1960 to Jan 2009	285	0	1.5	127	202	29

In-Fallow Water Balance Summary

Figure 1 HowLeaky C++ based graphical user interface

Development on the Window's based software continued up until about 2014 when funding was limited, and the C++ based user interface technologies became outdated and unmanageable. This prompted a new direction for development which was aimed at the "cloud". A limited beta version of a web-based ***HowLeaky*** software (http://howleaky.com.au) was previewed to testers in December 2018 with a final version expected to be released in 2020. The main benefit of this version includes improved accessibility, centralised data storage and extensive supporting metadata. The ***HowLeaky*** model has also been reused in several web and mobile-based software with minimalistic and highly customised user-interfaces (such as http://climateapp.net.au and http://soilwaterapp.net.au/) developed from 2014 onwards.

1.3 How it works

The ***HowLeaky*** model simulates the soil water balance (core model) and its effects on different agricultural and land use management practices (submodels) at a point-scale and on a daily time-step. The model uses daily climate data and a volumetric parameterisation of the soil layers to model the core components of soil water inflows, outflows and redistribution of water in the soil.

Runoff is calculated as a function of daily rainfall, soil water deficit, surface residue, crop cover and surface roughness. Soil water is updated on a daily basis by any rainfall exceeding the daily runoff volume. Infiltration is partitioned into the 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 but only if the layer immediately below can hold the water. 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. Transpiration is represented as a function of pan evaporation, green cover (or leaf area) and soil moisture. It is removed from the profile according to the current depth and distribution of roots. Transpiration can only dry a profile layer to its defined wilting point. Soil evaporation is based on a two-stage evaporation algorithm. After infiltration has occurred, it is assumed that drying occurs at potential rate up to a user defined limit. After this limit is reached, the second and slower stage of soil evaporation commences. Evaporation will remove soil water from the two upper profile layers and drying continues below wilting point to the user specified air-dry limit. The sum of transpiration and soil evaporation can never exceed pan evaporation on any day.

Soil erosion is estimated on days of runoff using a modified version of the universal soil loss equation (USLE) that expresses soil erosion as a function of runoff volume, cover, soil erodibility, management practice and topography.

Vegetative growth can be modelled using either a "Dynamic Leaf Area index model (LAI, Ritchie, 1972)", a "Crop-Cover model" or a "Crop-Factor model". The LAI-crop model predicts crop phenology, leaf area and dry matter using functions of transpiration, transpiration efficiency, potential evaporation, intercepted radiation, radiation use efficiency, daily temperature and photoperiod. Growth is reduced due to water or temperature stress. Crop yield is related to total dry matter and plant water use around flowering.

A daily balance of crop residue weight on the surface is maintained. At harvest, above-ground crop dry matter is added to crop residue. Residue decays over time or is incorporated by tillage. Decay and residue incorporation by tillage is related to residue type and tillage implement. Percent cover is estimated from residue weight on a daily basis. Tillage applies only to the LAI model and affects both the weight of crop residue and surface roughness. Crop planting and tillage dates can either be input by the user or generated automatically subject to user defined planting or tillage criteria. For automatic planting, the user must define a range of criteria that defines crop type, planting rainfall, minimum soil water content and the possible range of planting dates for the crop. Planting will occur when all criteria are satisfied. The automatic tillage model will perform the selected tillage operation based on accumulated rainfall.

The Cover-model is much simpler than the LAI model and imports predefined profiles of green-cover, residue cover and root depth, while using the same method to estimate transpiration as the LAI model. Biomass and crop-yield are estimated using a water use efficiency factor and harvest index. The Crop-factor model is even simpler than the LAI and Cover models. It does not estimate yield and lumps evaporation and transpiration together into a single evapotranspiration output.

HowLeaky can simulate irrigation using a range of management options including a water limiting supply through a ring-tank component. This includes different scheduling options for irrigating within a "window", while a crop is growing, or through predefining a sequence of dates and amounts. It allows the user to define different trigger options, refill points and minimum days between irrigations. Different options exist to estimate runoff and evaporation losses and to deal with ponding.

HowLeaky contains submodels for simulating pesticide and fertiliser (N and P) losses and solute leaching. These submodels are optional and are activated by defining their input parameters and connecting them to a simulation. They are called during the daily time-step using outputs from the daily water balance.

The pesticide submodel is used to track dissipation of pesticides in the soil, crop stubble and vegetation; and estimates pesticide concentrations in runoff partitioned between soluble and sediment bound phases.

The phosphorus submodel is used to calculate dissolved, particulate and total phosphorus before calculating bioavailable phosphorus. It includes empirical functions for estimating the enrichment of total P in sediment and concentration of soluble P in runoff. The model uses the widely available phosphorus buffering index test (PBI) to estimate soil adsorption of P (P buffering), which affects the soluble P concentration in runoff.

A Nitrate N submodel contains a subset of three separate models for calculating dissolved N in runoff, dissolved N in leaching and particulate N in runoff. These models do not employ a nitrate "volume-balance" and they do not "route" nitrate through the soil. Instead, they represent a simplified approach whereby (in most cases) a nitrate concentration profile in the soil is predetermined and used to respond to runoff and drainage events by estimating what nitrate would be removed during those events. Two additional variations to this methodology have been included for estimating dissolved N in runoff after fertiliser applications.

A generic solute submodel is used to estimate solute leaching and works by providing an initial solute concentration across the soil layers (defined using a range of options) as well as rainfall and irrigation water solute concentrations. A mixing coefficient is also provided to then route the solute through the soil profile when rainfall or irrigation is enough to cause drainage.

1.4 Underlying assumptions

The major underlying assumptions of ***HowLeaky*** are not unique to this model. There is a plethora of water balance models that share these assumptions.

The first major underlying assumption is that ***HowLeaky*** is mechanistic in that the overall structure of the model is based on the laws of physics but individual processes within the model may be empirical.

The second major underlying assumption of ***HowLeaky*** is that it is a daily timestep model. The choice of a daily timestep during model development was made because daily weather data are more freely available than data at timesteps of less than one day (for example, hourly data). Since all biophysical processes are simulated on a daily timestep, some processes (for example, event erosion) may be poorly predicted for some individual events. However, as shown in Littleboy et al. (1992a), long-term predictions can be acceptable.

The third major underlying assumption is that ***HowLeaky*** is a one-dimensional model in that it simulates a single point in a landscape without any consideration of lateral surface or subsurface flow of water. Therefore, it is generally only applicable for field-sized areas with homogeneous soils, vegetation, topography and climate.

1.5 Key source models

The algorithms and submodels in ***HowLeaky*** have been derived from a wide range of source models. Key submodels are highlighted in Table 1 below.

Table 1: Key source models used in the HowLeaky model

Source model name	Used for	Reference
CREAMS	Soil water redistribution	Knisel, 1980
USDA Curve Number approach	Surface runoff	Knisel, 1980; LaSeur, 1976
Ritchie's two-stage evaporation algorithm.	Evaporation	Ritchie, 1972
EPIC model	Leaf area development	Williams, 1983
Revised Universal Soil Loss Equation	Soil erosion	Renard, Foster, Weesies, McCool, & Yoder, 1993
CREAMS/GLEAMS	Pesticide	Leonard, Knisel & Still 1987; Knisel, 1980

1.6 Strengths and weaknesses of *HowLeaky* and *PERFECT*

The strengths of ***HowLeaky*** and ***PERFECT*** are that:

- the underlying model is based on a cropping systems model that contains dynamic water balance, crop growth, soil erosion, fallow management and planting decision submodels in an integrated framework. Many crop growth models only simulate crop growth for a single growing season and ignore fallow periods. ***HowLeaky*** and ***PERFECT*** can simulate sequences or rotations of different crops and fallow management practices for a wide range of cropping systems.
- weather data requirements for ***HowLeaky*** and ***PERFECT*** are readily obtainable from government sources such as the “SILO” climate database (www.longpaddock.qld.gov.au/silo). The minimum weather data set is daily rain and average monthly radiation, pan evaporation and temperature.
- soil parameters in ***HowLeaky*** and ***PERFECT*** have a physical basis and can be measured or estimated using a range of techniques. Strategic field sampling of soil water, rainfall simulation and specific laboratory analyses are key tools to derive model inputs. A range of surrogate models to estimate input parameters from more readily available soil survey data are also available.
- the model is capable of performing long-term simulations using historical daily rainfall data to permit the user to study the long-term variability in model outputs (for example, water balance, erosion, and crop yield).
- extensive validation of ***PERFECT*** has been performed and published in the scientific literature. This validation has been undertaken with data from seven locations, 17 soils and 45 farm management options (for example, different crops, tillage practices and fertiliser options). There have been over 420 experimental years of data used. In addition, using other datasets, there are numerous publications describing the validation of models that were later to become submodels of ***HowLeaky*** and ***PERFECT***. Some examples of submodels of

HowLeaky and ***PERFECT*** that have been compared with field data include the CREAMS and GLEAMS water balance models (Silburn & Freebairn, 1992; Connolly, Carroll, Frances, Silburn, Simpson & Freebairn, 1999; Connolly, Kennedy, Silburn, Simpson & Freebairn, 2001) and various soil erosion models (Freebairn et al., 1989).

- ***HowLeaky*** and ***PERFECT*** have been widely applied. There is a large number of published applications including defining erosion-productivity relationships (Littleboy et al. 1992b; Littleboy, Cogle, Smith, Yule & Rao, 1996c); evaluating the effects of cropping systems on runoff, recharge, erosion and yield (Carroll, Littleboy & Halpin, 1992; Hayman, 1992; Abbs, 1994; Hayman & Kneipp, 1995; Abbs & Littleboy, 1998); evaluating surface management options (Freebairn, Littleboy, Smith & Coughlan, 1991; Littleboy, Cogle, Smith, Yule, & Rao, 1996a; Littleboy, Sachan, Smith & Cogle, 1996b; Littleboy et al., 1996c; Cogle, Littleboy, Rao, Smith & Yule, 1996); evaluating the effects of crop and pasture rotations on runoff, erosion and recharge (Lawrence & Littleboy, 1990; Fraser & Waters, 2004; Thornton, Cowie, Freebairn, & Playford, 2007; Robinson et al., 2010); quantitative land evaluation (Grundy, Littleboy & Heiner, 1992; Thomas, Gardner, Littleboy & Shields, 1995; Littleboy, Smith & Bryant, 1996d; Littleboy 1998); assessing risk of soil compaction (Littleboy, McGarry & Bray, 1998); estimating the hydrological effects of tree clearing (Williams, Bui, Gardiner, Littleboy & Probert, 1997); and design of land-based effluent disposal systems (Gardner, Littleboy & Beavers, 1995).

The weaknesses of ***HowLeaky*** and ***PERFECT*** are that:

- they are one-dimensional models that simulate a single point in a landscape and do not consider partial area runoff processes or lateral movement of water. They are only applicable for field-sized areas with homogeneous soils, vegetation, topography and climate.
- they are daily timestep models in that all biophysical processes are simulated on a daily timestep. As a result, some processes that occur at a smaller timestep may in some circumstances be poorly predicted.
- they do not have a fully interactive management module (such as the one included in the ***APSIM*** model; McCown, Hammer, Hargreaves, Holzworth, & Freebairn, 1996) to enable the user to trigger management decisions (for example, planting, fertiliser, irrigation and tillage) from a range of biophysical criteria or to write external code.
- tall canopies are considered equally as effective in reducing runoff as short canopies and crop residues.

1.7 Major differences between the *HowLeaky* and *PERFECT* algorithms

There are several differences between algorithms used to simulate water balance processes in ***PERFECT*** and ***HowLeaky.*** The main differences are that:

- in ***PERFECT***, crop cover is a linear function of LAI, up to 100% cover. In ***Howleaky***, cover has a non-linear relationship with LAI (cover = 100 * $(1\text{-}e^{-c.LAI})$ where c is 0.6);
- in ***PERFECT***, deep drainage uses the algorithm from the GLEAMS model (Leonard, Knisel & Still, 1987), whereas ***HowLeaky*** drains all available water in a soil layer, up to a defined maximum (mm/day);
- in ***PERFECT***, potential soil evaporation (SE) is a function of LAI (Ritchie, 1972), whereas ***HowLeaky*** equates potential SE with the difference between potential evapotranspiration and transpiration (that is, unsatisfied evaporative demand);
- in ***PERFECT***, dry matter accumulation is a non-linear function of water stress, whereas it is linear in ***HowLeaky;***
- in ***PERFECT***, leaf area accumulation is a non-linear function of water stress, whereas it is linear in ***HowLeaky***;

- in ***PERFECT***, crop residue declines exponentially with time, whereas ***HowLeaky*** uses a dynamic algorithm based on rainfall and temperature similar to that used in the ***SWAT*** model (Soil and Water Assessment Tool, https://swat.tamu.edu); and
- ***HowLeaky*** contains new modules for simulating irrigation, pesticides, phosphorus, solutes and nitrates.
- Note that all the original ***PERFECT*** algorithms are still available in ***HowLeaky*** and activated through setting appropriate model options.

2 Structure of the *HowLeaky* model

2.1 Inputs, outputs and submodels

The ***HowLeaky*** model consists of a base model for assessing the soil-water balance and a range of optional submodels for different types of cropping and management practices. This structure is described in **Figure 2** which shows the base model, optional submodels, inputs and outputs.

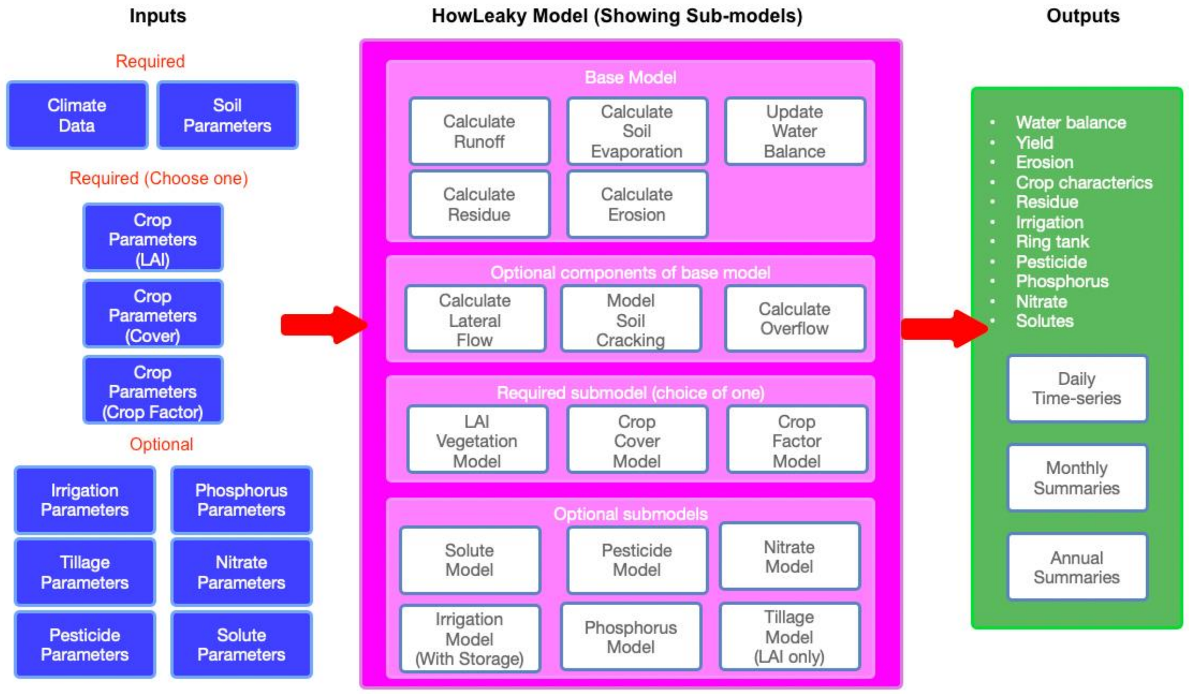


Figure 2: Structure of HowLeaky showing main model, submodels, inputs and outputs

HowLeaky's input parameters are grouped according to each submodel for soil, crop, irrigation, phosphorus, tillage, nitrate, pesticide, solutes and model options. These input parameter groupings are listed in detail in Appendices 1 to 10. Associated with each individual input parameter (and stored in XML datafiles) is metadata showing previous values, modification status and developer comments. While designed to aid in the sharing of input data between modellers, historically these metadata capabilities have not been well adopted. The latest development of the web-based ***HowLeaky*** model will see all these parameter-sets stored in the cloud (relational database) with an emphasis on promoting better parameter documentation and sharing of datasets.

The ***HowLeaky*** model-structure is highly modular and configurable which is in part due to the need to maximise computational performance though avoiding redundant calculations. Simulation does not automatically invoke all components of the model, nor does it generate all outputs. Rather, activation of the optional submodels for solutes, pesticide, nitrate, irrigation, phosphorus and tillage only occur when their input parameters are provided. Activation of optional components of the base model is through setting appropriate model options. Activation of a cropping/vegetation submodel is compulsory, though the user has a choice of LAI, Cover or Crop-Factor options.

HowLeaky's outputs include daily time-series, monthly statistics and annual summaries that are grouped according to the submodels (Appendix 11). This includes output sets for water-balance, crop characteristics, erosion, residue, irrigation, storage performance, pesticide, phosphorus, nitrate and solutes. To maximise computation performance and minimise the memory footprint, daily time-series are only generated if activated by the user via the user interface. However, the monthly and annual summaries are automatically generated for whichever submodels are activated.

2.2 Operation

Running a simulation in ***HowLeaky*** involves three separate processes of initialisation, iterating through a daily time-step that calls each submodel, and finalising the outputs (**Figure 3**). For any day of the simulation, management operations are defined by comparing the current simulation date with any key dates defined through the submodels' input parameters. For example, planting can be defined at a date each year or within a "planting window".

Since date calculations are "expensive" in numerical computing, the start and end dates are converted to Julian Days (integer days). Simulations then proceed from day one to day "n" (number of days between start and end dates). The Simulation Engine calls "Simulate Day" for each day in the simulation, and daily outputs are generated at the end of each day (and stored in a time-series when required). Summary outputs including annual averages and percentiles are generated once simulations for day "n" have been completed.

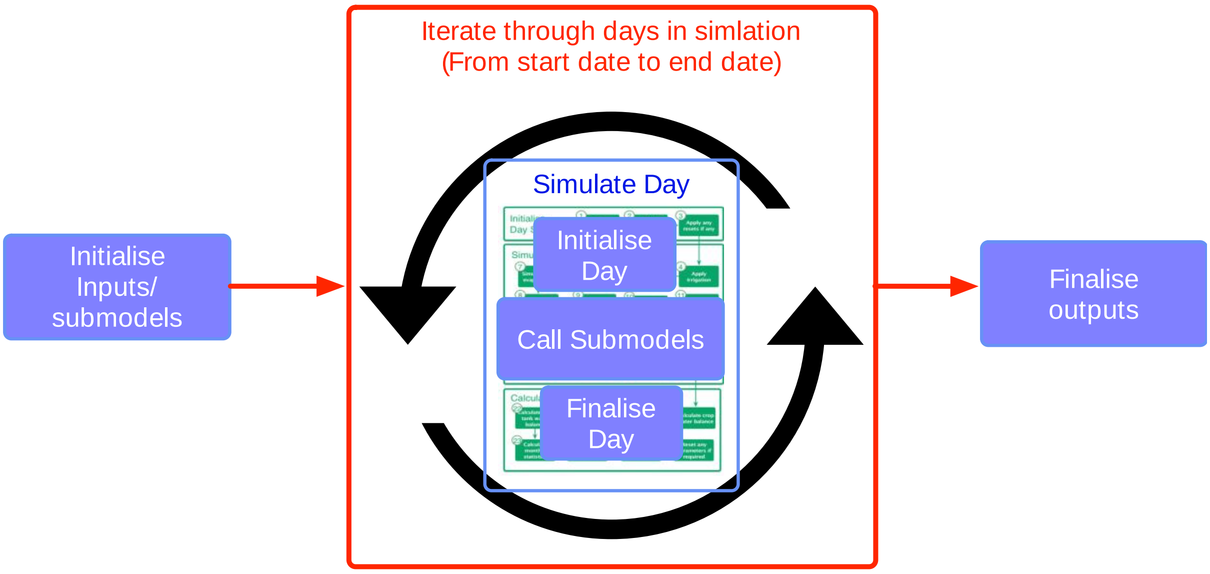


Figure 3 Operation of the HowLeaky model

2.2.1 Simulation initialisation

Simulation initialisation is a multistep process which includes loading the input parameters and climate data from their data-files into memory, as well as defining the initial "State" of the model. Specifically, these processes include:

- loading input parameters for each submodel;
- loading climate data;
- setting all temporary variables to 0;
- initialising all outputs parameters including activated daily time-series;
- defining the start and end dates of the simulation; and
- initialising the soil properties including defining soil-water limits for each layer and setting the starting soil moisture and crop residue conditions.

The options for defining the initial “State” in ***HowLeaky*** are limited. Unfortunately, ***HowLeaky*** does not allow users to “run-up” (define the initial state) a simulation by using the endpoint of a previous simulation as the starting point of a new simulation. Initial soil-water conditions are defined as 50% of the total soil water capacity. Fallow conditions are assumed to initially exist for LAI-based cropping and management submodels are initialised according to their input parameter specifications.

2.2.2 Simulate day

The “*Simulate Day*” operation is the central routine (main simulation loop) of the simulation model. It is called on a day-by-day basis from the initial start date (as defined through the simulation setup options) through to the last date defined in the climate records. Individual operations that occur during “*Simulate Day*” are shown in **Figure 4** which are grouped according to initialisation, submodel and output categories.

Daily simulation commences by updating the date variable (extracting day, month and year), loading rainfall, temperature and evaporation values, resetting any daily totals, and applying any “resets” (specified in the inputs) if necessary. Simulation then proceeds to update the daily water balance before executing any submodels which may be active. Some key points to note are that:

- the optional irrigation submodel (*Step five – Apply Irrigation*) precedes the water-balance calculations effectively assuming that irrigation occurs at the start of the day. This is required as un-infiltrated irrigation water is treated as “effective rainfall” which is central to the water balance calculations.
- transpiration must be calculated (through the “*Step 9 -Grow vegetation* function”) before the water balance is finalised.
- “*Step 10 – Update soil water balance*” performs the calculations on soil water storage and drainage in each layer.
- “*Step 11 – Model ring tank*” is executed when the ring-tank option is enabled in the irrigation parameters. This limits the amount of water available for irrigation. The available water supply is queried in “*Step five – Apply irrigation*”.
- the water balance is adjusted in “*Step 20- Remove Irrigation evap losses”* to account for any evaporation losses from pre-infiltrated irrigation water. This amount is added to the evaporation from the soil profile.
- “S*tep 14 – Calculate erosion*” is not optional.
- “*Step 19 – Calculate lateral flow*” is only performed if this option is selected in the options settings. It is “off” by default and is used to account for additional losses on steep slopes.
- “*Step 26 – Calculate volume balance errors*” is used as an internal check to ensure that the water-balance is consistent and not gaining or losing water. Note however, that a volume balance error will exist if soil-water resets are applied in “*Step 4*”
- “*Step 27 – Update output parameters*” is used to update any daily time-series outputs that the user may have selected in the user interface.

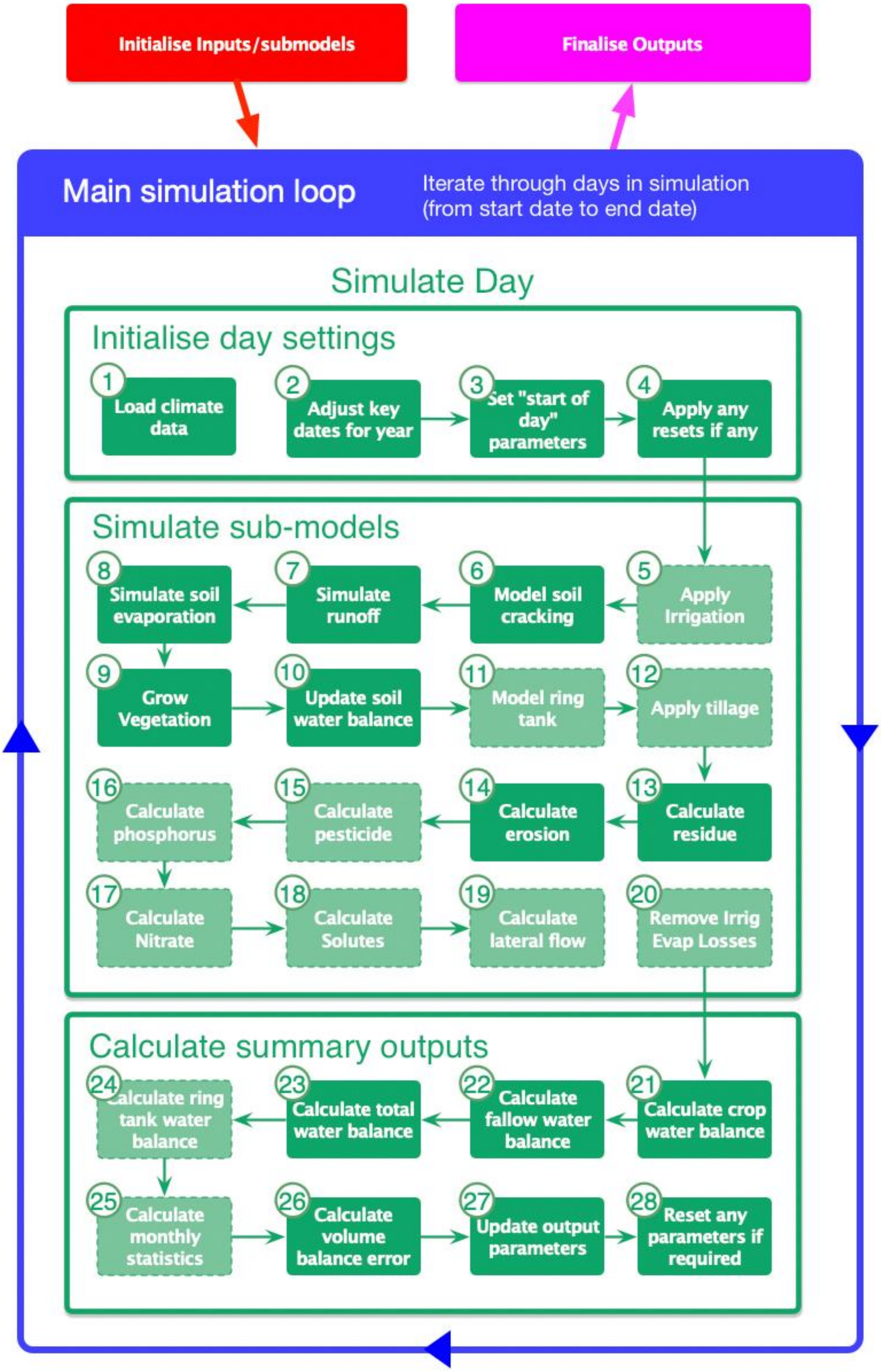


Figure 4 Sequence of operations involved in the "Simulate Day" method called on a daily-timestep. Optional steps are shown in a faded colour.

3 Soil-water balance calculations (Base model)

Much of the text in this section relating water balance, infiltration, drainage, runoff and soil evaporation has been sourced from the ***PERFECT*** V3 Manual (Littleboy et al., 1999). Where necessary, it has been updated with some changes in notation and order of calculations.

3.1 Water balance

The water balance base-model (Steps 7-10 in **Figure 4**) calculates the volume of water in the soil on a daily time-step and is assumed to be one-dimensional, or at a single point in the field. On any day in the simulation, the calculation of the soil water balance includes calculating the individual components of:

- rainfall,
- rrrigation,
- runoff,
- overflow,
- evaporation,
- transpiration,
- lateral flow,
- deep drainage, and
- soil water ('change in').

Figure 5 shows a simplified structure of the linear cascading model of the soil water balance. Rainfall and irrigation are the only inputs while evaporation, transpiration and deep drainage are the main loss components. Overflow and lateral flow are optional loss components that can be included in the simulation but not are usually calculated.

Soil water status is updated daily after accounting for runoff. Infiltration is the amount of rainfall left after all runoff has occurred. An additional algorithm to determine water infiltrating to lower profile layers through cracks has been included and is discussed in Appendix 13. Infiltration is added to the top layer of the soil profile. Soil water redistribution is calculated using a linear cascading technique based on the procedure developed for CREAMS (Knisel, 1980). Redistribution of water from the lowest soil horizon is assumed lost to the soil as deep drainage.

In this idealised structure, each soil horizon is represented by a "bucket". A pipe in each bucket allows water to drain only when the level of water is above the pipe. A tap in the pipe limits the rate at which water moves from one bucket to the next. Capacity of each bucket is equivalent to the saturated water content (SAT) of the soil horizon. Height of the pipe in each bucket represents the drained upper limit (DUL) of the soil horizon while a tap in each pipe symbolises the maximum drainage rate of the soil horizon. This type of water balance model is appropriate for the daily time-step rainfall data that are readily available. More detailed soil water balance models exist but such models invariably require rainfall data measured at more frequent intervals (for example, hourly data).

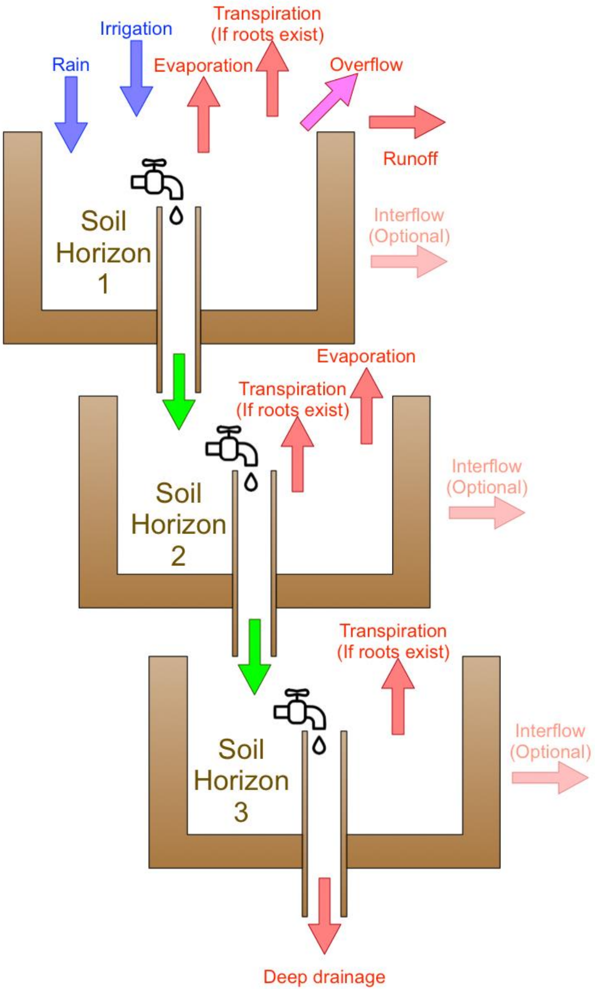


Figure 5 Soil Water distributions showing inputs, outputs and limiters

The different components of the water balance will now be discussed in turn.

3.2 Calculate infiltration/drainage and soil water redistribution

Soil water redistribution and deep drainage are calculated using the functions from CREAMS (Knisel, 1980). During calculations, water is routed down each layer i by first calculating the available soil water in each layer SW_i (relative to wilting point, mm) and testing to see if any layer drainage ($drain_i$) can occur. Layer drainage can only occur when the soil water is greater than the drained upper limit (DUL_i) and is calculated as the minimum of the saturated hydraulic conductivity and drainable porosity.

To calculate SW_i in each layer, the algorithm iterates through each layer of the soil profile i, from top to bottom. Note that the calculation of SW_i is different for the top two layers as these are affected by different rates of evaporation.

If in the first layer:

$$SW_i = SW_i + seepage_i - (soil\_evaporation - se22) - layer\_transpiration_i \tag{3-1}$$

where:

- $seepage_i$ is the daily drainage from the layer (mm);
- $soil\_evaporation$ is the daily evaporation from the layer (mm);
- $se22$ is stage II soil evaporation (mm); and,
- $layer\_transpiration_i$ is the daily transpiration via roots from the layer (mm).

If in the second layer:

$$SW_i = SW_i + seepage_i - layer\_transpiration_i + red_i - se22 \tag{3-2}$$

where:

- red_i is the amount of water in cracks calculated from the optional soil cracking module (mm).

If in all other layers:

$$SW_i = SW_i + seepage_i - layer\_transpiration_i + red_i \tag{3-3}$$

Then to calculate drainage (mm) in each layer ($drain_i$), the drainage factor $swcon_i$ (0 to 1 range and unitless) must first be determined. This remains a constant throughout the simulation and can be estimated during initialisation from the soil input parameters. It determines the proportion of soil water above field capacity draining to a lower profile layer (Knisel, 1980). This factor is based on the input maximum layer drainage value $ksat_i$ and assumes that the drainage factor equals unity when the condition $(SW_i\text{-}DUL_i) \leq ksat$ is true.

The formula for $swcon_i$ is:

$$swcon_i = \frac{2 \times ksat_i}{SAT_i - DUL_i + ksat_i} \tag{3-4}$$

where:

- SAT_i is the soil saturation limit relative to wilting point (mm); and,
- DUL_i is the soil drained upper limit (field capacity) relative to wilting point (mm).

Once available water and drainage factor in each layer is determined, the layer drainage can be calculated so long as $SW_i > DUL_i$:

$$drain_i = swcon_i \times (SW_i - DUL_i) \tag{3-5}$$

If $drain_i > ksat_i$:

$$drain_i = ksat_i \tag{3-6}$$

If $drain_i < 0$:

$$drain_i = 0 \tag{3-7}$$

3.2.1 Calculate runoff

Surface runoff (mm) is calculated using a variation of the USDA Curve Number approach, similar to that used in CREAMS (Knisel, 1980) and originally proposed by Williams and LaSeur (1976). The original Williams approach considered runoff depth as a function of rainfall and soil water deficit. This has been adjusted to account for the effects of crop and residue cover. Effectively, runoff (mm) becomes a function of rainfall and a runoff retention parameter:

$$runoff = \frac{(effective\_rain - 0.2 \times S)}{(effective\_rain + 0.8 \times S)} \qquad \text{3-8}$$

where:

- $effective\_rain$ is daily rainfall plus any un-infiltrated irrigation amounts (mm); and,
- S is the runoff retention parameter (described shortly).

The runoff retention parameter S is analogous to the maximum potential infiltration in 24 hours or the soil water deficit. Therefore, a larger volume of runoff occurs at a low soil water deficit and little runoff occurs at a high soil water deficit. Predicted runoff will equal the daily rainfall when the soil water deficit is zero (that is, the soil is saturated).

The estimation of the retention parameter S involves a series of functions initially based on the input curve number CN2(bare) parameter as depicted in **Figure 6**.This CN2(bare) parameter represents the rainfall versus runoff response for average antecedent moisture conditions and for bare and untilled soil. This curve number $cn2$ is modified within ***HowLeaky*** to account for crop cover, surface residue cover and surface roughness each day.

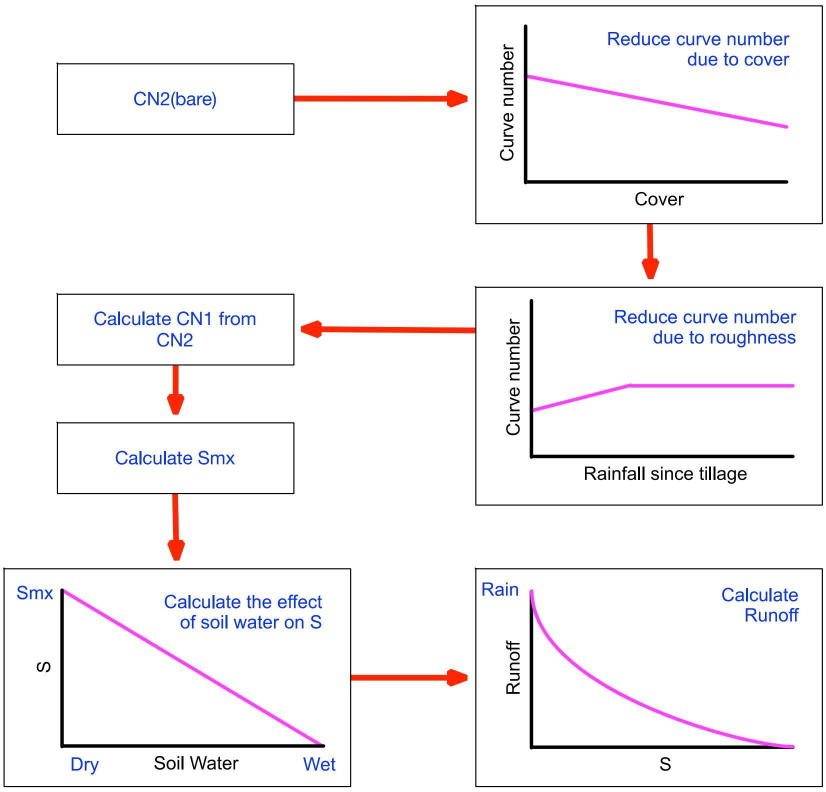


Figure 6 Flow diagram of curve number method

The retention parameter is related to available soil water using a modified form of the equation from Knisel (1980):

$$S = smx \times (1.0 - sumh20) \tag{3-9}$$

where:

- smx is the maximum value of S during dry antecedent conditions; and,
- $\mathrm{sumh20}$ is the accumulation of soil moisture in each layer (mm).

HowLeaky has two options for calculating smx and $\mathrm{sumh20}$. The first is using the original ***PERFECT*** algorithms and the second is using an unpublished variation from Brett Robinson in 2011 (not documented but based on CREAMS, Equations i-3 and i-4, with a fix for "*oversize* smx *at low CN*"). These are discussed shortly in Sections 3.2.4 and 3.2.5.

However, before smx and $\mathrm{sumh20}$ can be calculated, both the cover and tillage effects on curve number ($\mathrm{cn2}$) must be calculated:

3.2.2 Cover effects on curve number

To account for the effects of ground cover on curve number:

$$\begin{aligned} cn2 = cn_{bare} - cnred \\ \times Min\left(1, cover_{crop} + cover_{totalresidue} \times (1 - cover_{crop})\right) \end{aligned} \tag{3-10}$$

where,

- $\mathrm{cn_{bare}}$ is the curve number for soil with no cover (defined as an input in the soil file); and,
- cnred is the maximum reduction in curve number at 100% cover (also an input in the soil file).

Various attempts to determine curve number for different soil types and management strategies have been undertaken. For example, USDA-SCS (1972) described procedures to derive curve number for a range of soils, while Rawls, Onstad and Richardson (1980) attempted to adjust curve number for surface cover. However, in these examples, any adjustment in curve number to account for surface cover is constant during the simulation. Hence curve number is often considered as a static parameter. In ***PERFECT*** and ***HowLeaky***, effects of cover on curve number are estimated from a relationship originally developed from a rainfall simulator data (Glanville, Freebairn & Silburn, 1984). Since ***PERFECT*** maintains a daily balance of both crop and residue cover, curve number is a dynamic parameter that changes on a daily basis during the simulation.

3.2.3 Tillage effects on curve number

There is a defined relationship between curve number and surface roughness. Therefore, tillage type and rainfall-since-tillage can be used as predictors of surface roughness. The influence of roughness on runoff was incorporated into the model by developing a relationship between curve number and cumulative rainfall-since-tillage (Littleboy et al., 1996a). The adjustment occurs only when rainfall-since-tillage is less than the $\mathrm{RainToRemoveRoughness}$ (mm) input parameter. If this condition is true, then:

$$cn2 = cn2 + roughness\_ratio \times MaxRedInCNDueToTill \times \left(\frac{rain\_since\_tillage}{RainToRemoveRoughness} - 1\right) \tag{3-11}$$

where:

- roughness_ratio is an input value representing the value of the curve number for soil with no cover;
- MaxRedInCNDueToTill is the maximum reduction in curve number due to tillage; and,
- rain_since_tillage (mm) is the amount of rainfall since the last tillage.

As the CN-cover relationship on Equation 3-10 had tillage and cover effects combined (i.e. high cover had less tillage and vice versa in the tillage/catchment study) using a tillage effect in addition to a cover effect is double accounting.

3.2.4 Option1 for calculating smx and sumh20

If using the ***PERFECT*** option, smx based on “CREAMS” (CREAMS, p.14, Equations i-3 and i-4) is first calculated. The weighting factor allows for more emphasis to be placed on the upper soil profile layers when determining S from the current soil water status. The maximum value of S is determined from Knisel (1980):

$$smx = 254 \times \left(\frac{100}{cn1} - 1.0\right) \tag{3-12}$$

where:

- cn1 is the curve number for the driest antecedent moisture condition.

It is related to cn2 through a polynomial expression from Knisel (1980):

$$\mathrm{cn1} = -16.91 + 1.348 \times \mathrm{c{-}n2} - 0.01379 \times \mathrm{cn2}^2 + 0.0001177 \times \mathrm{cn2}^3 \tag{3-13}$$

Then, sumh20 is calculated by iterating through each soil layer and accumulating soil moisture:

$$sumh20 = \sum_{i=1}^{i=n} wf_i \times \frac{Max(PAW_i, 0)}{SatLimit_i} \tag{3-14}$$

where:

- $\mathrm{Max}(\mathrm{PAW}_i,0)$ is the maximum of plant available moisture in the layer (relative to wilting point) and 0 (mm);
- $\mathrm{SatLimit}_i$ is the saturation limit of the layer (mm); and,
- wf_i is a depth retention weighting factor for the layer based on layer thickness (explained in Equation 3-18 and Appendix 12.6).

3.2.5 Option 2 for calculating smx and sumh20

If using the modified calculation of smx (Brett Robinson, 2011 - unpublished):

if $\mathrm{cn2}>83$ (where the relationship is linear above $\mathrm{cn2}=83$), then:

$$smx = 6 + (100 - cn2) \times 6.66 \tag{3-15}$$

else:

$$smx = 254.0 - \frac{265.0 \times e^{0.17\times(cn2\,-50)}}{265.0 + (e^{0.17\times(cn2\,-50)} + 1)} \tag{3-16}$$

Calculations in this option are performed relative to the air-dry limit ($\mathrm{AirDryLimit_i}$), whereas those in option 1 were relative to wilting point. This is to overcome a perceived issue where CREAMs and other models tend to discount/underestimate the runoff retention parameter for water content. Then $\mathrm{sumh20}$ is calculated by iterating through each layer i:

$$sumh20 = \sum_{i=1}^{i=n} wfi \times \frac{PAW_i + AirDryLimit_i}{(SatLimit_i + AirDryLimit_i)} \tag{3-17}$$

where:

- wfi is the weighting factor for each layer which is calculated using the method of Knisel (1980):

$$wf_i = 1.016\left(e^{-4.16\times\frac{depth_i}{depth_{max}}} - e^{-4.16\times\frac{depth_{i+1}}{depth_{max}}}\right) \tag{3-18}$$

where:

- $\mathrm{depth_{max}}$ is the depth to the bottom of the lowest defined soil layer.

3.2.6 Runoff from irrigation

Runoff losses from irrigation can be explicitly predefined (as a percentage of irrigation water applied) in the irrigation inputs to account for the high runoff losses that can occur during some forms of irrigation. If this option is used, then these losses must be added to the calculated runoff:

$$runoff = runoff + runoff_{irrigation} \tag{3-19}$$

where:

- $\mathrm{runoff_{irrigation}}$ is runoff from irrigation that is predefined in the input parameters as a percentage of applied irrigation water.

3.3 Soil evaporation

Evaporation of water from the soil surface is based on ’Ritchie's (1972) two-stage evaporation algorithm. After infiltration, drying occurs at a potential rate up to a specified limit (Stage I), then at a rate reflecting diffusion processes that are assumed proportional to the square root of time (Stage II). This relatively simple model was originally developed by Ritchie (1972) using lysimeter data. Although the model is conceptually simple, it is quite complex in an operational sense. Readers are referred to the original paper by Ritchie (1972) which provides a flow diagram of all the interactions between Stage I and Stage II drying.

In ***HowLeaky***, soil evaporation removes water from the two upper soil horizons and drying can continue below wilting point. The soil in layer 1 dries to the defined air-dry moisture content. In layer 2, the soil dries to a moisture content at the midpoint between air-dry and wilting point. ***HowLeaky*** includes two modifications to the original Ritchie (1972) model. Firstly, Stage I drying recommences after any rainfall event but is limited by the amount of infiltration. This contrasts with the original algorithm (Ritchie 1972), where all cumulative Stage II drying had to be replenished by infiltration before Stage I drying could recommence. Secondly, effects of crop residue on potential Stage I drying rate have been incorporated, based on data reported in Adams, Arkin and Ritchie (1976). As demonstrated below, potential soil evaporation is calculated from pan evaporation and crop cover (thus crop canopy cover reduces soil evaporation). Pan evaporation is used within ***HowLeaky*** rather than techniques such as Penman-Monteith or Priestly-Taylor because in the original ***PERFECT*** model, the dynamic wheat and sunflower crop models were developed using pan evaporation as the potential evaporative demand factor.

To start the calculations, potential soil evaporation must be estimated based on the amount of bare soil and crop cover. Soil evaporation is calculated from the relevant crop model with different estimations for LAI, Cover and Crop-Factor models.

If the LAI model is used, then $potential\_soil\_evaporation$ is dependent on the following criteria, with two calculation methods defined through the input parameters (***PERFECT*** or *Robinson* methods):

if the ***PERFECT*** methodology for calculating $potential\_soil\_evaporation$ and LAI is less than 0.3 is used then:

$$potential\_soil\_evaporation = pan\_evap \times (1 - green\_cover) \tag{3-20}$$

Else if the ***Robinson*** methodology (undocumented) is used or if LAI is greater than 0.3:

$$potential\_soil\_evaporation = pan\_evap \times (1 - crop\_cover) \tag{3-21}$$

where:

- $green\_cover$ (proportion) is calculated based on the current value of LAI and $crop\_cover$ is the current highest value of $green\_cover$ during this crop.

If the ***PERFECT*** methodology is used, then $green\_cover$ is:

$$green\_cover = Min\left(\frac{LAI}{3.0}, 1\right) \tag{3-22}$$

Else if the modified *Robinson* methodology is used:

$$green\_cover = 1 - e^{-0.55 \times (LAI + 0.1)} \tag{3-23}$$

Finally, $crop\_cover$ is calculated as:

$$crop\_cover = Max(green\_cover, crop\_cover) \tag{3-24}$$

If the Cover model is used, then:

$$potential\_soil\_evaporation = pan\_evap \times (1 - total\_cover \times 0.87) \qquad 3\text{-}25$$

where:

- the factor of 0.87 is derived from a similar routine used in the ***APSIM*** model (personal communication, D. Rattray, 2003).

If the Crop-Factor model is used, then $\mathrm{potential\_soil\_evaporation}$ becomes 0, as it is accounted for in the evapotranspiration amount calculated later on in the crop submodel:

$$potential\_soil\_evaporation = 0 \qquad 3\text{-}26$$

Potential soil evaporation rate is further modified for crop residue effects using the relationship given by Adams et al. (1976). ***HowLeaky*** assumes that different types of crop residue have the same effect on soil evaporation. Therefore, if $\mathrm{total\_crop\_residue}$ is greater than 1, then an adjustment is needed:

$$\begin{aligned} &potential\_soil\_evaporation \\ &\quad = potential\_soil\_evaporation \times e^{\frac{-0.22 \times total\_crop\_residue}{1000}} \end{aligned} \qquad 3\text{-}27$$

where:

- $\mathrm{total\_crop\_residue}$ is the total crop residue (t/ha).

In a special case when irrigating and using the “Ponding” option (defined in the input parameters):

$$soil\_evaporation = potential\_soil\_evaporation \qquad 3\text{-}28$$

Stage I drying commences after infiltration. Stage I soil evaporation will equal the potential soil evaporation rate until the cumulative Stage I drying exceeds the value of the parameter U (the upper limit of Stage I drying). Cumulative Stage I drying is reduced by any amount of infiltration that occurs. When this limit is exceeded, Stage II drying commences based on Ritchie (1972).

Stage II drying on any day will be less than the daily potential soil evaporation rate. In very dry profiles, the rate of Stage II drying will be restricted by the lack of soil water in the top two layers of the profile. $Cona$ represents the slope of the Stage II drying curve when cumulative soil evaporation is plotted against the square root of time.

The methodology involves estimating the cumulative soil evaporation (mm) due to Stage I and Stage II drying (denoted $\mathrm{sse1}$ and $\mathrm{sse2}$ respectively). These are accumulated over successive days with the latest values updated from the previous day’s values. These values are then used to calculate the depth of Stage I and Stage II soil evaporation for the current day (denoted $\mathrm{se1}$ and $\mathrm{se2}$ respectively).

To start the calculations, the previous day’s values of $\mathrm{sse1}$ and $\mathrm{sse2}$ may need to be adjusted to account for any infiltration that has occurred today. For example, yesterday’s $\mathrm{sse1}$ needs to be reset if infiltration occurred today and yesterday’s $\mathrm{sse2}$ should be reset if infiltration exceeds $sse1$.

Therefore, if $\mathrm{infiltration}>0$, then:

$$sse2_{yesterday} = Max(0, sse2_{yesterday} - Max(0, infiltration - sse1_{yesterday})) \tag{3-29}$$

where $\mathrm{sse1}_{\mathrm{yesterday}}$ is:

$$sse1_{yesterday} = Max(0, sse1_{yesterday} - infiltration) \tag{3-30}$$

Then recalculate the days since rainfall (dsr) using the Ritchie (1972) relationship for Stage II drying to account for these adjustments:

$$dsr = \left(\frac{sse2}{Cona}\right)^2 \tag{3-31}$$

Then test for Stage I drying. If $\mathrm{sse1}<\mathrm{U}$, then Stage I evaporation for today is calculated by setting $\mathrm{se1}$ equal to potential soil evaporation but limited by U:

$$se1 = Min(potential\_soil\_evaporation, U - sse1_{yesterday}) \tag{3-32}$$

It is also limited by the total available water relative to the air-dry limit in the first layer [2] ($\mathrm{AirDryLimit}_0$) of soil:

$$se1 = Max(0, Min(se1, PAW_0 + AirDryLimit_0)) \tag{3-33}$$

where:

- PAW_0 and $\mathrm{AirDryLimit}_0$ are both relative to wilting point and adding them together represents the total available water relative to the air-dry limit in the first layer of soil.

Then to update the accumulated Stage I drying for today:

$$sse1 = sse1_{yesterday} + se1 \tag{3-34}$$

Then check if potential soil evaporation is satisfied by Stage I drying. If not, calculate Stage II drying ($\mathrm{sse2}$). Two conditions must be tested: condition 1 where $\mathrm{potential\_soil\_evaporation}>\mathrm{se1}$ and condition 2 where $\mathrm{potential\_soil\_evaporation}\leq\mathrm{se1}$.

Condition 1: where $\mathrm{potential\_soil\_evaporation}>\mathrm{se1}$

If infiltration occurs on the day, and $\mathrm{potential\_soil\_evaporation} > \mathrm{se1}$ (that is, a deficit in evaporation) and $\mathrm{se2}>0$, then that portion of $\mathrm{potential\_soil\_evaporation}$ not satisfied by $\mathrm{se1}$ should be second Stage. This can be determined by $\sqrt{\mathrm{dsr}} \times \mathrm{Cona}$ with any remainder ignored. If $\mathrm{sse2} = 0$, then use Ritchie's (1972) empirical transition constant (0.6).

---

[2] Subscript of 0 is used to denote first layer to reflect how it is applied in the computer code.

Therefore, if $\mathrm{sse2} > 0$, then[3]:

$$se2 = Min(potential\_soil\_evaporation - se1\,, Cona \times \sqrt{dsr} - sse2) \tag{3-35}$$

otherwise:

$$se2 = 0.6 \times (potential\_soil\_evaporation - se1) \tag{3-36}$$

Calculate Stage II evaporation from layers 1 and 2 ($\mathrm{se21}$ and $\mathrm{se22}$ respectively). Any Stage I evaporation will equal infiltration and therefore no net change in soil water for layer 1 (that is, use $\mathrm{PAW}_1 + \mathrm{AirDryLimit}_1$ to determine $\mathrm{se21}$). Then using subscripts 0 and 1 to denote the layer's 1 and 2 respectively:

$$se21 = Max(0, Min(se2,\ PAW_0 + AirDryLimit_0)\,) \tag{3-37}$$

and:

$$se22 = Max(0, Min(-se2 - se21,\ PAW_1 + AirDryLimit_1)\,) \tag{3-38}$$

Then recalculate $\mathrm{se2}$ when $\mathrm{se2\text{-}se21} > \mathrm{PAW}_2 + \mathrm{AirDryLimit}_2$:

$$se2 = se21 + se22 \tag{3-39}$$

Finally, update the cumulative values of Stage I and Stage II soil evaporation, for today:

$$sse1 = U \tag{3-40}$$

$$sse2 = sse2_{yesterday} + se2 \tag{3-41}$$

dsr must also be recalculated to account for these changes:

$$dsr = \left(\frac{sse2}{Cona}\right)^2 \tag{3-42}$$

---

[3] Note that it has been suggested that there could be an error in the application of Cona as described by these formulas. By definition of slope, $Cona = \frac{\Delta \mathrm{sse2}}{\Delta\sqrt{\mathrm{dsr}}}$. Over a timestep of one day, $\mathrm{Cona} = \frac{\Delta \mathrm{sse2}}{\Delta\sqrt{\mathrm{dsr}}} = \frac{\mathrm{se2}}{\sqrt{\mathrm{dsr}} - \sqrt{(\mathrm{dsr}-1)}}$. Hence $\mathrm{se2} = \mathrm{Cona} \times \left[\sqrt{\mathrm{dsr}} - \sqrt{(\mathrm{dsr}-1)}\right]$. This calculation of se2 behaves as according to Ritchie's description, with the $\left[\sqrt{\mathrm{dsr}} - \sqrt{(\mathrm{dsr}-1)}\right]$ multiplier showing a value less than one, declining with increasing dsr (personal communication, A. Vieritz, 2019).

Condition 2: where $potential\_soil\_evaporation \leq se1$

If $potential\_soil\_evaporation \leq se1$:

$$sse1 = U \tag{3-43}$$

In this case, there is no Stage I drying therefore stage II evaporation must be calculated and the water from soil layers 1 & 2 must be removed.

To do this, dsr must be incremented before recalculating all Stage II components:

$$dsr = dsr + 1.0 \tag{3-44}$$

$$se2 = Min(potential\_soil\_evaporation, Cona \times \sqrt{dsr}) - sse2) \tag{3-45}$$

$$se21 = Max(0, Min(se2, PAW_0 + AirDryLimit_0)) \tag{3-46}$$

$$se22 = Max(0, Min(se2 - se21, PAW_1 + AirDryLimit_1)) \tag{3-47}$$

Recalculate $se2$ when $se2\text{-}se21 > PAW_2 + AirDryLimit_2$:

$$se2 = se21 + se22 \tag{3-48}$$

Finally, update the cumulative Stage II soil evaporation for today:

$$sse2 = sse2_{yesterday} + se2 \tag{3-49}$$

Then calculate total soil evaporation as the sum of Stage I and Stage II drying:

$$soil\_evaporation = se1 + se2 \tag{3-50}$$

4 Vegetation submodels

There are three generic submodels for simulating crop or vegetation growth in ***HowLeaky***:

- Leaf Area Index model (LAI),
- Cover model, and
- Crop-Factor model.

These models differ in how they estimate crop development, cover and biomass. The LAI model is the most dynamic, as vegetative cover (leaf area) is calculated on a daily basis while the other two models use a predefined cover profile. The LAI and Cover model utilise the same calculations for estimating transpiration, while the Crop-Factor model estimates a lumped evapotranspiration amount.

4.1 Calculate transpiration

If the LAI or Cover models are used, transpiration is calculated using a cover limited proportion of potential transpiration (mm) and soil water and root density conditions in each soil layer. This is done by first calculating the potential daily transpiration rate, and then by iterating through the soil profile and calculating water supply and root density ratios in each layer. These are then multiplied together to estimate the transpiration in each layer before summing these amounts to calculate the total transpiration for that day.

To start the calculations, the potential daily transpiration limited by ground cover ($\mathrm{potential\_transpiration}$) must be calculated:

$$potential\_transpiration = Minimum(pan\_evaporation \times green\_cover, \\ pan\_evaporation - soil\_evaporation) \tag{4-1}$$

where:

- $\mathrm{green\_cover}$ is a fraction.

If using the LAI model and water-logging options are enabled, and the soil is waterlogged:

$$potential\_transpiration \\ = potential\_transpiration \times WaterLoggingFactor1 \tag{4-2}$$

where:

- $\mathrm{WaterLoggingFactor1}$ is an adjustment factor (unitless) defined in the input parameters.

Then the layer transpiration should be initialised to 0, by iterating through each layer i:

$$layer\_transpiration_i = 0 \tag{4-3}$$

Then calculate the soil water supply index $\mathrm{mcfc_i}$ in each i-th layer, which will later be used to estimate a “water supply index”:

$$mcfc_i = \frac{PAW_i}{DUL_i} \tag{4-4}$$

where:

- $\mathrm{DUL_i}$ represents the drained upper limit in that soil layer.

Then, introduce a “water supply index” variable called $\mathrm{supply_i}$. This variable is calculated for each layer depending on the value of $\mathrm{mcfc_i}$. Two conditions are considered. For condition 1, if $\mathrm{mcfc_i}$ is greater than or equal to a limiting soil-water factor defined in the user input parameters (that is, the soil water proportion for no crop stress, $\mathrm{SWPropForNoStress}$):

$$supply_i = 1 \tag{4-5}$$

otherwise (condition 2):

$$supply_i = \frac{mcfc_i}{SWPropForNoStress} \tag{4-6}$$

Next, the root penetration factor ($\mathrm{root\_penetration_i}$) is calculated before calculating a root-density index ($\mathrm{density_i}$):

$$root\_penetration_i = Min\left(1\,, \frac{Max(root\_depth - depth_0, 0)}{thickness\_layer\_1}\right) \tag{4-7}$$

if $\mathrm{depth_{i+1}}$ is greater than 300mm:

$$density_i = Max\left(0, \left(1 - 0.5 \times Min\left(1, \left(\frac{depth_0 - 300}{root\_depth_{MAX} - 300}\right)\right)\right)\right) \tag{4-8}$$

otherwise:

$$density_i = 1 \tag{4-9}$$

Then the transpiration from each layer i is calculated by multiplying the potential transpiration by the root-density and water-supply factors:

$$layer\_transpiration_i = density_i \times supply_i \times potential\_transpiration \tag{4-10}$$

It is necessary to check that total transpiration does not exceed potential transpiration. To check this, the estimated total transpiration (all soil layers) is calculated and stored in a temporary variable denoted “psup”. If psup is greater than the potential transpiration, then scale back the layer transpiration values by a ratio of “potential” over “estimated” total transpiration. That is, psup is greater than potential transpiration:

$$layer\_tranpiration_i = layer\_transpiration_i \times \frac{potential\_transpiration}{psup} \tag{4-11}$$

Finally, calculate the total transpiration:

$$total\_transpiration = \sum_{i=1}^{i=n} layer\_transpiration_i \tag{4-12}$$

4.2 Dynamic Leaf Area Index (LAI) vegetation model

The dynamic models predict crop phenology, leaf area and dry matter using functions of transpiration, transpiration efficiency, potential evaporation, intercepted radiation, radiation use efficiency, daily temperature and photoperiod. Growth is reduced due to water or temperature stress. Crop yield is related to total dry matter and plant water use around flowering. A daily balance of crop residue weight on the surface is maintained. At harvest, above-ground crop dry matter is added to crop residue. During the fallow, residue is decayed or incorporated by tillage. Decay and residue incorporation by tillage is related to residue type and tillage implement. Percent cover is estimated from residue weight on a daily basis.

On any day of the simulation, the LAI model will include logical operations to check for planting, calculate crop progress, calculate leaf area and biomass development, and test for crop death or harvesting (**Figure 7**). That is, when no crop exists, the model will check for planting. When a crop exists, transpiration will be calculated, and the conditions tested to see if the crop survives. Harvest conditions are then tested. When crop growth occurs, key functions are called to calculate stress factors, leaf area, crop cover, biomass and root growth.

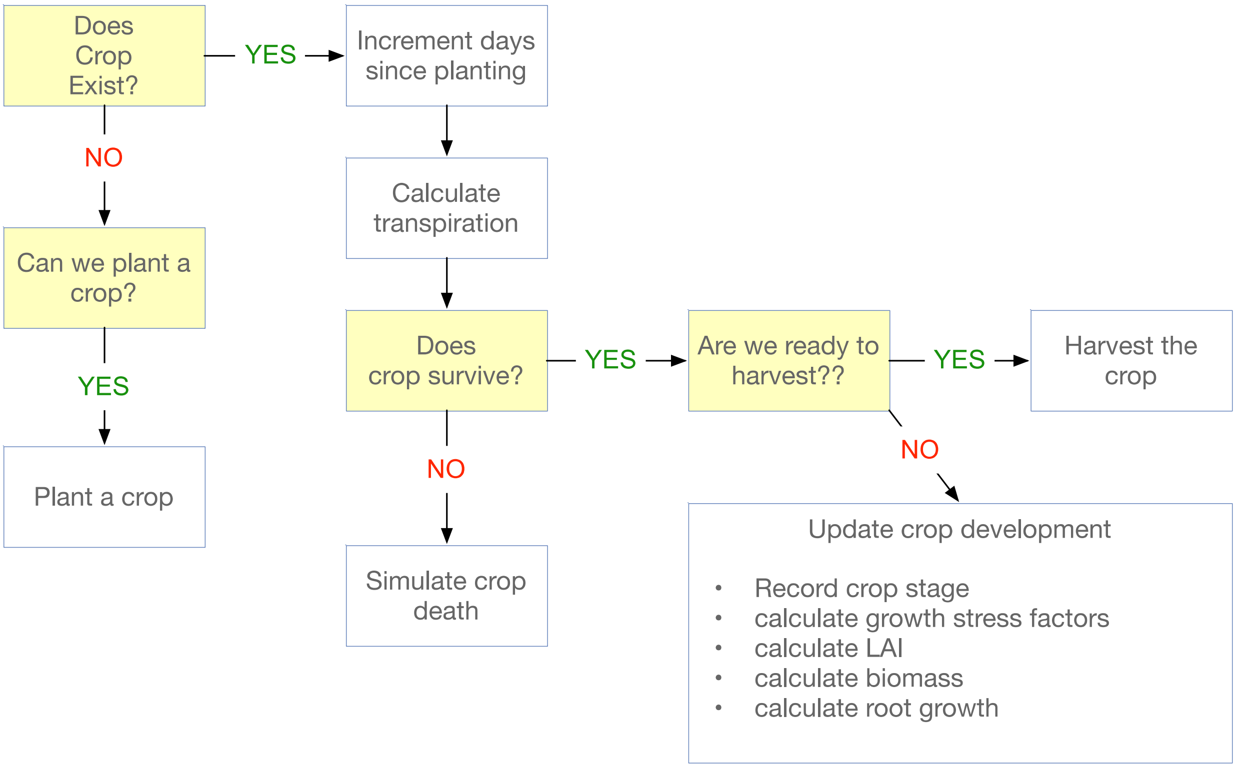


Figure 7: "SimulateCrop" algorithm for LAI model

4.2.1 LAI-model planting algorithm

The ***HowLeaky*** LAI model provides a range of input options to define when a crop is planted, and LAI development commences. The simplest options include forcing a crop to plant at a predefined date, while other options allow complex planting logic to be defined. This includes rules to define a planting window of opportunity; checking fallow, soil water and planting rain conditions; as well as satisfying multi-crop and multi-plant criteria. Later versions of ***HowLeaky*** provide graphical tools to deal with this complexity and allow users to investigate the conditions of all these rules at any point in time to determine why a crop may or may not have been planted.

In the following discussion on planting logic conditions and planting-day initialisation, a range of input and monitored/calculated variables are introduced and include (in order of appearance):

- FixedPlantDay and FixedPlantMonth are input parameters representing planting day and month (integer values) for the “fixed-planting” option.
- days_since_harvest is a monitored variable representing the number of days since the last crop was harvested, which is reset on the harvest day, and incremented daily.
- MinimumFallowPeriod is an input parameter (days) to define the minimum length of fallow before planting can be considered.
- SowingDelay is an input value (in days) representing the number of consecutive rain free days that must be considered before planting.
- fallow_planting_rain is a monitored variable assessing the amount of rain (mm) that has occurred during the fallow period.
- RainfallPlantingThreshold is an input parameter (mm) used to define how much rainfall is required to have occurred during the fallow before planting is permissible.
- PAW is a monitored estimate of soil water (mm) above wilting point (plant available water).
- SoilWaterReqToPlant is an input parameter (mm) representing a minimum amount of plant available soil water (relative to wilting point) to assess if planting is permissible.
- MinSoilWaterTopLayer and MaxSoilWaterTopLayer are input parameters (mm) used to define the minimum and maximum soil water conditions (relative to wilting point) that must occur in the top layer of the soil before planting is permissible.
- days_since_planting is a monitored variable representing the number of days that the crop has been growing, which is reset at planting and incremented daily.
- soil_water_at_planting is a monitored value (mm) updated on the day of planting representing the soil moisture conditions at planting (relative to wilting point) and used later on in calculating a “fallow efficiency” estimate.
- heat_units is the cumulative heat-sum value (^{o}C) calculated as the sum of daily maximum temperature minus a “base temperature” (defined in the crop input parameter file representing the minimum temperature for plant growth) during crop-growth.This value is updated daily as the crop is growing.
- heat_unit_index is a calculated index (from 0 to 1) representing the growth progress of the crop. It is calculated by dividing the heat_units by the input parameter DegreeDaysToMaturity (total heat units for crop anthesis).
- max_calc_lai is a monitored value representing the maximum calculated value of leaf area index estimated during a plant growth cycle.
- hufp is a calculated value representing “yesterday’s” heat unit factor (HUF) as defined by *Equation 2.198 from EPIC.*
- killdays is a monitored value representing the number of days where a crop is perceived as being “water-stressed”, defined as when the water stress index (wsi) is greater than a water stress threshold input value (WaterStressThreshold).
- rotation_count is a monitored value representing the number of consecutive rotations (plantings) of a particular crop.

- SoilWaterResetValueAfterPlanting is an input value (defined as a percentage of PAWC) that is an optional setting the user can enable to reset soil water to a pre-conceived value on the day of plating.

During each day of the simulation while fallow conditions exist, the model will test to see if conditions meet the sowing criteria. This includes testing whether:

- planting rules equal “Fixed Annual Planting”:
    - returns true if FixedPlantDay equals current day and FixedPlantMonth equals current month.
- planting rules equal “Plant in Window”:
    - satisfies window conditions:
        - checks if current date falls within planting window.
    - satisfies fallow conditions:
        - checks if days_since_harvest is greater than MinimumFallowPeriod.
    - satisfies planting rain:
        - compares consecutive rain free days against SowingDelay input and ensures that fallow_planting_rain is greater than RainfallPlantingThreshold.
    - satisfies soil water conditions:
        - ensures that total PAW is greater than SoilWaterReqToPlant , and that PAW in the top layer is between MinSoilWaterTopLayer and MaxSoilWaterTopLayer.
    - satisfies multi-plant in window conditions:
        - checks to see if another crop has already been planted in this window.

If the planting criteria are satisfied, the model will then call the “Plant” function which initialises a number of crop parameters and outputs. Operations include:

- updating the total number of plantings;
- setting current crop;
- reseting days_since_planting;
- reseting dry matter;
- reseting root depth;
- capturing soil_water_at_planting;
- reseting crop cover;
- reseting heat_unit_index, heat_units, max_calc_lai, hufp, killdays to 0;
- telling simulation that today is a “Plant Day”;
- incrementing rotation_count;
- checking to see if user has nominated to “Update SoilWater at Planting”;
- reseting PAW in each layer based on SoilWaterResetValueAfterPlanting input; and
- updating management flags and history.

4.2.2 LAI model growth stress factor calculations

When simulating crop growth using the LAI model, it is necessary to continually account for any temperature stress or water stress that the plant may be experiencing. This can be done by calculating a growth_regulator factor that equals the dominating stress weighting, as estimated from a temperature stress index (tsi) and a water stress index (wsi). The growth_regulator will appear in the two methodologies presented in Section 4.2.3 and is used to limit leaf area development.

The temperature stress index is calculated using Equation 2.235 from EPIC (Williams, 1983):

$$tsi = sin\left(0.5 \times \pi \times \frac{temperature - BaseTemp}{OptimalTemp - BaseTemp}\right) \tag{4-13}$$

Water Stress Index is calculated as:

$$wsi = \frac{total\_transpiration}{potential\_transpiration} \tag{4-14}$$

Then the growth regulator is calculated:

$$growth\_regulator = Minimum(Minimum(1, tsi), wsi) \tag{4-15}$$

4.2.3 LAI model leaf area development

The ***HowLeaky*** LAI model contains two methods for estimating leaf area development. The first is based on the functions from the EPIC model (Williams, 1983) which was used in ***PERFECT***. The second method for estimating LAI is the modified option of Robinson (unpublished). Robinson identified that the original function never allowed LAI to achieve max LAI under no-stress conditions.

4.2.3.1 Option 1 – PERFECT method for estimating leaf area development

Using the original ***PERFECT*** methodology, LAI is calculated from user-defined inputs including: maximum LAI; proportion of growing season at which maximum LAI occurs; two pairs of points (LAI and proportion of growing season) that determine the shape of the LAI curve; and a senescence parameter (**Figure 8**). LAI development is driven by thermal time. An S-Curve function is used to define LAI development up to the time when maximum LAI occurs. After that time, a leaf senescence algorithm is used to reduce LAI.

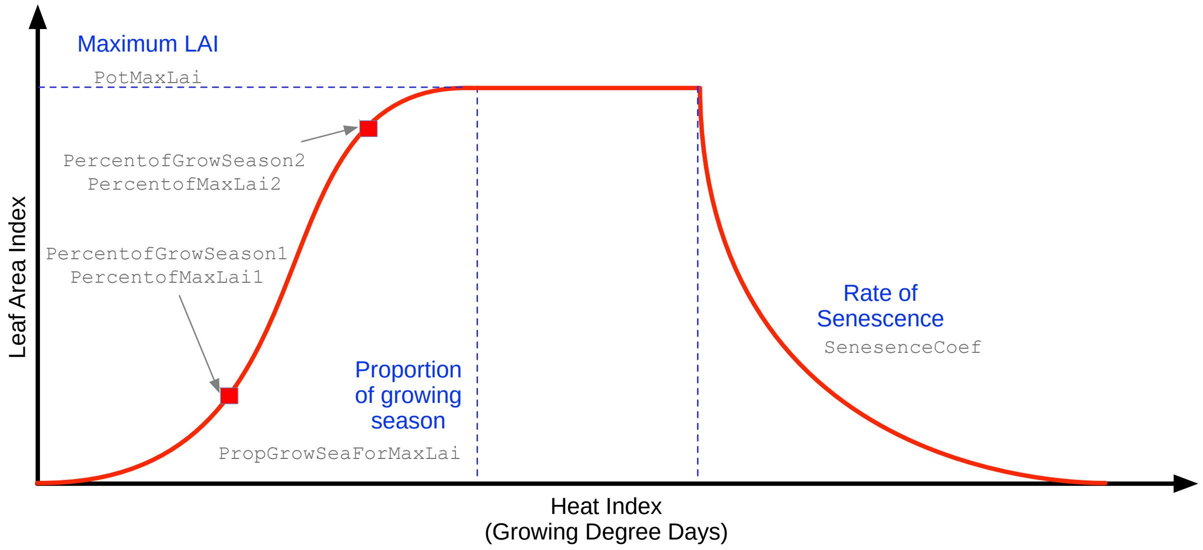


Figure 8: Potential leaf area development

Daily increment in LAI (dlai) development is calculated from maximum LAI, heat units, stress factors and shape parameters:

$$dlai = dHUF \times PotMaxLAI \times \sqrt{growth\_regulator} \tag{4-16}$$

where:

- dlai is the daily increment in LAI (m2 m-2);
- dHUF is the daily change in heat unit factor;
- PotMaxLAI is the user-defined (input parameter) maximum LAI (m2 m-2); and
- growth_regulator is the most limiting stress factor (water or temperature) calculated in Section 4.2.2.

4.2.3.2 Option 2 – Robinson method for estimating leaf area development

The second method for estimating LAI is the modified option of Robinson (not published). Robinson identified that the original function underpredicted LAI. He simplified the equation:

$$dlai = dHUF \times PotMaxLAI \times growth\_regulator \tag{4-17}$$

Then:

$$lai = lai_{yesterday} + dlai \tag{4-18}$$

4.2.3.3 Shared calculations

Both methods require calculation of the daily change heat unit factor dHUF. This involves first calculating a heat unit index (HUI) derived from the EPIC model (Williams, 1983), representing the crop development progress in the season. In the model, leaf growth only occurs if HUI is less than PropSeasonForMaxLAI:

$$HUI = \frac{heat\_units}{DegreeDaysToMaturity} \tag{4-19}$$

where:

- DegreeDaysToMaturity is the target heat-sum used to define crop maturity in the growing season (ºC); and,
- heat_units are the cumulative daily heat-sum of average daily temperature minus a base temperature (defined as an input) (ºC) and calculated as:

$$heat\_units = heat\_units + Maximum(temperature - BaseTemp, 0) \tag{4-20}$$

where temperature is the daily average temperature, BaseTemp is the reference temperature for the crop (defined through the input parameters) from which development occurs.

Then the heat unit factor HUF is calculated (while $\mathrm{HUI} < \mathrm{PropSeasonForMaxLAI}$) as:

$$HUF = \frac{HUI}{HUI + e^{LAICurveY1active - LAICurveY2active \times HUI}} \quad \text{4-21}$$

where:

- $\mathrm{LAICurveY1active}$ and $\mathrm{LAICurveY2active}$ are calculated during initialisation (Appendix 12)

Then the daily change in heat unit factor (dHUF) is:

$$dHUF = HUF - hufp \quad \text{4-22}$$

where:

- hufp is the previous days' value of the Heat Unit Factor. It is stored in the next step, for the next day's calculations:

$$hufp = HUF \quad \text{4-23}$$

These functions are only used to define LAI development up to the time when maximum LAI occurs (as defined through the input parameter). After that time, a leaf senescence algorithm is used to reduce LAI:

$$lai = max\_calc\_lai \times \left(\frac{1 - HUI}{1 - PropSeasonForMaxLAI}\right)^{SenesenceCoefficient} \quad \text{4-24}$$

where:

- $\mathrm{SenesenceCoefficient}$ and $\mathrm{PropSeasonForMaxLAI}$ are input parameters.

4.2.4 LAI model biomass calculations

These calculations are used to estimate biomass using EPIC type functions. First, calculate the daylength factor (hrlt) (from ***PERFECT*** – described in Appendix 14):

$$hrlt = GetDayLength() \quad \text{4-25}$$

Then track the change in the daylength factor (dhrlt):

$$dhrlt = hrlt_{today} - hrlt_{yesterday} \quad \text{4-26}$$

Then calculate the effective radiation use efficiency ($\mathrm{effectiverue}$). Initially, define it as the value from the input parameters ($\mathrm{RadiationUseEfficiency}$):

$$effectiverue = RadiationUseEfficiency \quad \text{4-27}$$

If the user employs the water logging option and the soil is waterlogged:

$$effectiverue = RadiationUseEfficiency \times WaterLoggingFactor2 \tag{4-28}$$

where:

- WaterLoggingFactor2 is a unitless input parameter defined in the LAI crop file.

Then calculate biomass accumulation (drymatter in t/ha). If the original ***PERFECT*** options (which uses Equation 2.193 from EPIC) is used:

$$drymatter = drymatter_{yesterday} + growth\_regulator \times par \times effectiverue \times (1 + dhrlt)^3 \tag{4-29}$$

Calculate intercepted radiation (par). This assumes par is 50% of solar radiation with extinction coefficient of 0.65:

$$par = 0.5 \times solar\_radiation \times (1.0 - e^{-0.65 \times LAI}) \tag{4-30}$$

Alternatively, use the modified function from Robinson (not published):

$$par = 0.5 \times solar\_radiation \tag{4-31}$$

Then dry matter (Drymatter in kg/ha) is calculated:

$$Drymatter = drymatter + effectiverue \times par \times wsi \times tsi \times greencover \tag{4-32}$$

where:

- tsi and wsi are water and temperature stress indices calculated earlier in Equations 4-13 and 4-14.

4.2.5 LAI model root growth calculations

Root penetration and root density are required in the transpiration calculations (Equations 4-7 to 4-9). These require estimations of root depth on a daily basis. This is aggregated based on a constant rate of growth (DailyRootGrowth) defined in the input parameters:

$$root\_depth = root\_depth + DailyRootGrowth \tag{4-33}$$

where:

- root_depth is constrained between 0 and MaximumRootDepth (input parameter); and,
- DailyRootGrowth is an input parameter representing the daily root growth (mm/day).

4.2.6 Harvest

At harvest, the LAI model calculates both yield (t/ha) and crop residue (kg/ha), before finally calculating total residue cover (%):

$$yield\_kg\_per\_ha = HarvestIndex \times dry\_matter \times 10.0 \tag{4-34}$$

$$yield\_t\_per\_ha = \frac{yield\_kg\_per\_ha}{1000.0} \tag{4-35}$$

$$crop\_residue = crop\_residue + \left(dry\_matter - \frac{yield\_kg\_per\_ha}{10.0}\right) \times 0.95 \times 10.0 \tag{4-36}$$

This crop residue will also decay on this day when the residue functions are called.

4.3 Cover model

The cover model is much simpler than the LAI model by allowing users to predefine annual or multi-year profiles of green cover (% cover), residue cover (% cover) and root depth (mm). It uses the same algorithm for calculating transpiration as the LAI model but does not calculate crop growth, instead it infers this from the cover and root depth profiles. It is particularly useful for soil-water studies to estimate transpiration of continuous crop-fallow rotations over many decades and avoids the setup complexities of the LAI model. It can also handle complex cropping rotations by defining continuous cover profiles over multiple years. It has been reputed to be “the simplest and most reliable option for estimating transpiration for 99% of ***HowLeaky*** users” (personal communication, D. Freebairn, 2018). However, it will not estimate variable cover driven by climate variation and failed crops; thus, soil erosion will be underestimated in such years.

Inputs include time-series profiles of green cover, residue cover and root depth (**Figure 9**) along with parameters including fixed planting day (defined in Julian days) and an estimate of growing days to harvest. Unfortunately, planting and harvesting dates cannot be inferred from the green cover profile, as the algorithms derive from the ***PERFECT*** model and have never been updated.

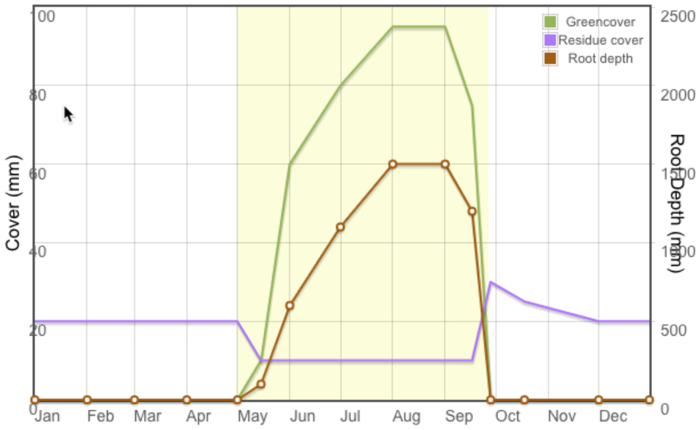


Figure 9 Sample green cover, residue cover and root depth profiles of the Cover model

A recently added option allows users to import the cover and root depth profiles from a data file with each profile defined as biomass values (kg/ha). When this option is selected, additional biomass conversion parameters are presented through the user interface to convert these values back to percentage cover or root depth. This was introduced by the Victorian Department of Primary Industries to allow ***DairyMod*** users (http://imj.com.au/dairymod/) to import outputs directly into ***HowLeaky***.

A "transpiration efficiency" parameter (kg/ha/mm of transpiration) is used to estimate "dry-matter" from crop transpiration, which when multiplied by "harvest index" is converted into crop yield. A soil-water stress parameter is also provided to define a critical soil water level to avoid crop stress. Finally, there are a range of multipliers for green-cover, residue cover and root depth to allow the modeller to scale the input profiles during calibration.

Figure 10 represents the sequence of events that are called during the "Simulate Crop" phase of the simulation. Unlike the LAI model, there are no conditional operators controlling different crop stages. Instead, green cover, residue cover and root depth are "interpolated" on a daily basis regardless of what the user has defined as the "growing period" through plant and harvest date input parameters. Nevertheless, these dates are checked daily to see if we can "plant" or "harvest" and to record "crop-stage" (which is a carry-over from the LAI model and has no functional capability in the Cover model). Transpiration and biomass are then calculated on a daily basis.

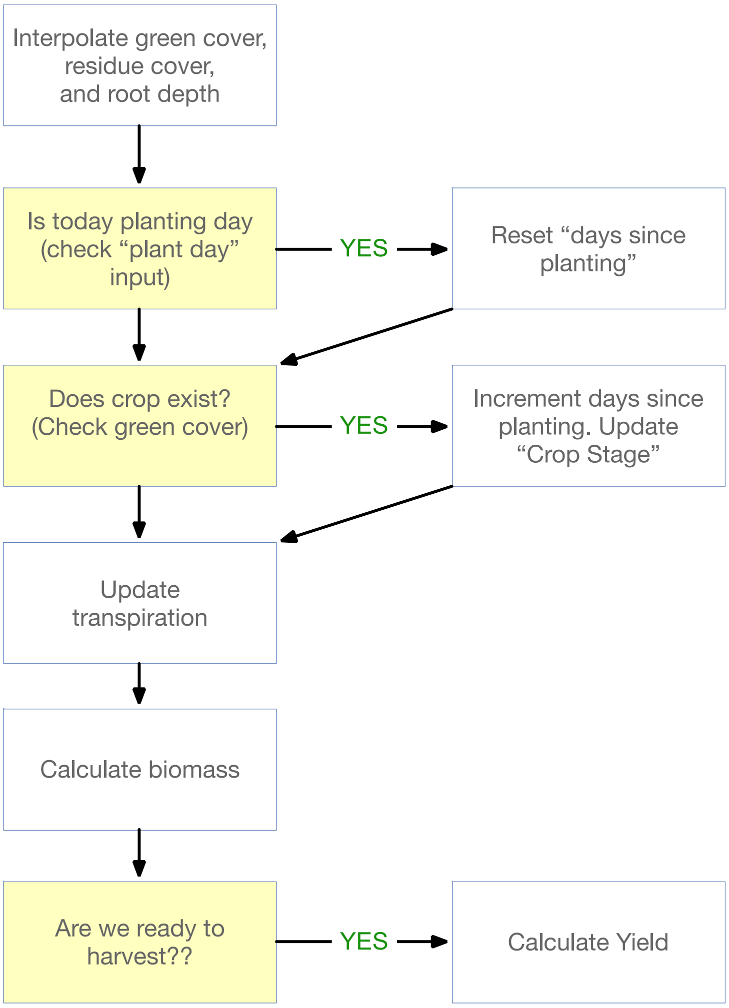


Figure 10 "SimulateCrop" algorithm for the cover model

4.3.1 Biomass calculations

The Cover model calculates total dry-matter by multiplying (cumulative) total transpiration across days of cover growth by WaterUseEfficiency (input parameter):

$$dry\_matter = WaterUseEfficiency \times total\_transpiration \tag{4-37}$$

4.3.2 Harvest (calculate yield)

At harvest, the Cover model calculates yield (t/ha) but does not recalculate residue cover (since residue cover is an input). Firstly, yield in kg/ha is calculated:

$$yield\_kg\_per\_ha = HarvestIndex \times dry\_matter \tag{4-38}$$

Note that this differs to the LAI calculation (Equation 4-34) in that it is not multiplied by 10:

$$yield\_t\_per\_ha = \frac{yield\_kg\_per\_ha}{1000.0} \tag{4-39}$$

4.4 Crop-factor model

The crop-factor model was introduced by the Western Australian Water Corporation to be compatible with other crop-factor based models used in Western Australia to look at irrigating cropping with wastewater. It was developed independently in the ***REPLENISH*** software (www.replenish.net.au) and transferred across into the Windows' based version of ***HowLeaky***. The Crop-Factor model calculates evapotranspiration based on FAO-56 recommendations for crop water use, and lumps evaporation and transpiration into a single output of "evapotranspiration".

The structure of the model is very simple, in that on a day-by-day basis, it interpolates crop-factor and root-depth values from the input parameters, updates root growth, and calculates evapotranspiration. Note that it stores this as "transpiration" with "evaporation" set as zero. This was hastily coded on the assumption that not many people would use this model and that its real purpose was for the validation of the ***REPLENISH*** software.

Inputs include time-series profiles of crop factors and root depth or a time-series of crop-factors and root-biomass imported from a data file. Regardless of the option used, these are accompanied by scaling factors to adjust the crop-factor or root depth measurements in unison.

4.4.1 Crop-Factor model evapotranspiration calculations

Calculations start off by estimating potential evapotranspiration. Note that in the following equations, the notation differs from what is used in the computer code. The code uses the wording "transpiration" instead of "evapotranspiration" to simplify integration with the existing water balance code. Evaporation is assumed to be zero during water balance calculations.

In the simulation input parameters, there is an option for defining the evaporation type. If this is set to use “pan evaporation”, then potential evapotranspiration can be estimated as:

$$potential\_evapotranspiration = pan\_evap\_coefficient \times evap \tag{4-40}$$

where:

- $\mathrm{pan\_evap\_coefficient}$ is the input parameter used to adjust daily pan evaporation (evap) to crudely convert this to ET_O for the crop-factor calculations.

Otherwise, it uses imported ET_O from specially download SILO data files calculated from FAO-56 (Allen, Pereira, Raes & Smith, 1998) specifications:

$$potential\_evapotranspiration = ETO \tag{4-41}$$

Then, this is multiplied by the daily crop factor (interpolated from the input crop factor profile) to calculate total (potential) evapotranspiration:

$$total\_evapotranspiration = potential\_evapotranspiration \times crop\_factor \tag{4-42}$$

Now this water will be extracted from the soil layers by first checking which layers have roots:

$$layers\_with\_roots = CalculateLayersWithRoots() \tag{4-43}$$

Then layer weightings ($\mathrm{weighting_i}$) are calculated to work out how much water is extracted from each layer. The lowest layer containing roots will be less than 1.0 (proportional with root penetration in that layer), while the higher layers will have a value of 1.0. Then iterate through each layer and reset layer evapotranspiration to zero. Finally, calculate the number of active layers, noting that the first two layers can extract water (through evaporation) regardless of the root depth.

Then work out how much water is extracted by iterating through each “active” layer:

$$amount\_to\_pull_i = total\_evapotranspiration \times weighting_i - carryover \tag{4-44}$$

where:

- $\mathrm{carryover}$ is the amount of possible evapotranspiration that is left unsatisfied by the previous layer, and carried over to the next layer.

The available water in each layer is equal to the soil water relative to wilting point:

$$avail_i = SW_i \tag{4-45}$$

If $amount\_to\_pull_i$ is less than $avail_i$, then:

$$evapotranspiration_i = amount\_to\_pull_i \tag{4-46}$$

and:

$$carryover = 0 \tag{4-47}$$

otherwise:

$$evapotranspiration_i = avail_i \tag{4-48}$$

$$carryover = amount\_to\_pull_i - avail_i \tag{4-49}$$

Then adjust total evapotranspiration for the day:

$$total\_evapotranspiration = total\_evapotranspiration - carryover \tag{4-50}$$

And finally, the cumulative evapotranspiration across days is:

$$\begin{aligned} accumulated\_evapotranspiration \\ &= accumulated\_evapotranspiration \\ &+ total\_evapotranspiration \end{aligned} \tag{4-51}$$

5 Irrigation submodel

The irrigation submodel in ***HowLeaky*** has evolved slowly from its original ***PERFECT*** model form (with a fixed amount and date) to have a limited range of options written specifically for the needs of key users/modellers/projects. Up until around 2008, only a few users were undertaking irrigation-based analyses in ***HowLeaky***. The ring tank submodel (which was first introduced in 2008 for an Indonesian study and refined in 2011) has been one of the most important developments for the irrigation module. It has since been used by a range of private consultants in studies on reusing wastewater for irrigation. The most recent modifications have allowed users to simulate sprinkler, flood and dripper practices by allowing losses to runoff and evaporation to be predefined.

The irrigation submodel adds the single component of “irrigation (mm)” to the water balance outputs as well as a wide range of outputs for storage behaviour (when ring tank option is enabled). Ring tank outputs include:

- evaporation losses (ml);
- seepage losses (ml);
- overtopping losses (ml);
- irrigation losses (ml);
- total losses (ml);
- captured runoff inflow (ml);
- rainfall inflow (ml);
- effective additional inflow (ml);
- total additional inflow (ml);
- total inflow (ml);
- ineffective additional inflow (ml);
- storage volume (ml); and
- ring tank storage level (%).

Irrigation application input parameters include different scheduling options for irrigating including: (a) within a “window”; (b) while a crop is growing; or (c) through predefining a sequence of dates and amounts. It allows the user to define different trigger options, refill points and minimum days between irrigations. Recent options allow runoff from irrigation to be predefined as a proportion of applied irrigation or through a sequence of dates and runoff amounts. Evaporation losses can also be predefined as a percentage of applied irrigation. Ponding effects can also be simulated.

Specifically, the model allows the user to:

- trigger an irrigation based on:
    - a fixed soil water deficit while a crop is growing;
    - a fixed soil water deficit within a predefined window;
    - a percentage of plant available water in the effective root zone while a crop is growing;
    - a percentage of plant available water in the effective root zone within a predefined window; and
    - predefined dates and amounts.
- apply an amount to irrigate to:
    - field capacity (Drained Upper Limit – DUL);
    - saturation;
    - a fixed amount applied;
    - DUL + 25% drainable porosity;
    - DUL + 50% drainable porosity;
    - DUL + 75% drainable porosity; and
    - DUL – 10% PAWC.
- specify a “rest” or “buffer” period between irrigations.
- predefine a proportion of water to be lost to runoff.

- predefine a proportion of water to be lost to evaporation (surface water evaporation or spray drift).
- simulate a ponding effect (soil evaporation = potential soil evaporation).
- simulate a ring-tank:
    - specify an additional inflow based on:
        - constant daily inflow rate; and
        - predefined sequence.
    - specify runoff capture rate.
    - specify delivery losses to field
    - specify evaporation losses.
    - specify seepage losses.

By specifying a ring-tank, it is effectively limiting the amount of water available for irrigation based on the water holding capacity of the storage, and the current storage level. Note that currently a ring tank cannot be shared between scenarios (paddocks), although this has been discussed as a future option.

5.1 Apply Irrigation (called daily)

Figure 11 demonstrates the sequence of events which are called when irrigation is activated and "Apply Irrigation" is called during daily simulation. Checks are first applied to see if conditions are suitable for irrigation. This depends on the input options selected but can include checking the irrigation window, checking if a crop is growing, checking when irrigation was last carried out, and testing soil water conditions. If conditions are favourable, then the model works out how much water the crop needs by checking the refill options and current soil water conditions. If a ring-tank module is defined, the supply is compared against what is needed for irrigation and water is extracted up to the required amount if possible. If runoff and evaporation options are applied, then these components are also extracted before finally delivering the remaining water to the field. This water is then distributed through the soil layers.

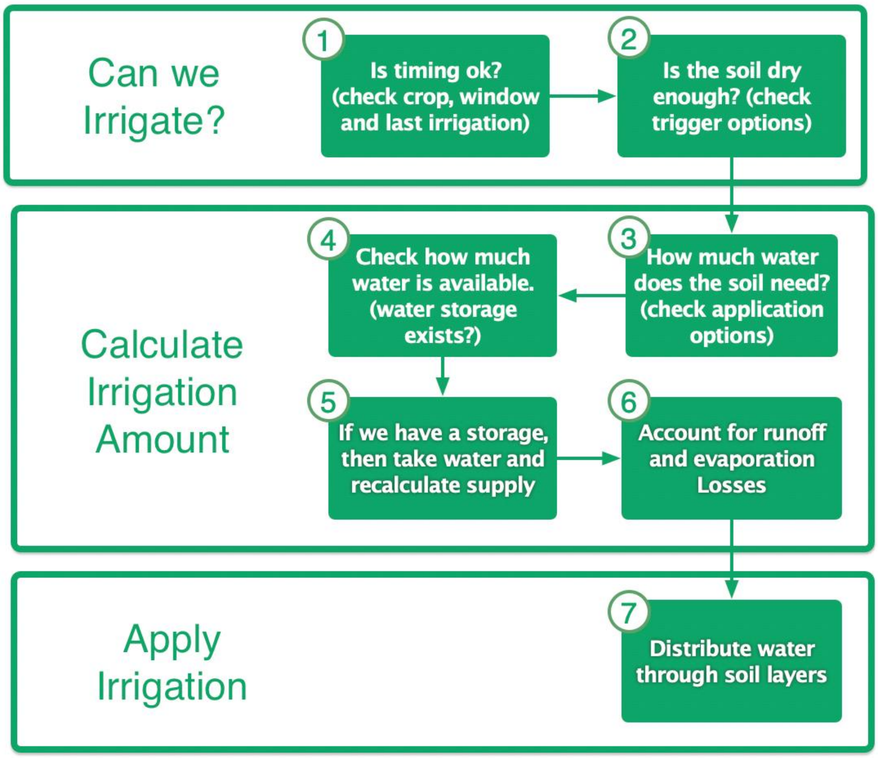


Figure 11: Logic use when irrigating

Note that in the case of runoff and evaporation options being applied, water is effectively “pushed” into each layer and ignores the drainage rate of each layer. This is an artefact of the legacy ***PERFECT*** code from which this algorithm is derived.

5.2 Main calculations

Several input and calculated/monitored parameters are introduced in the following section and include (in order of appearance):

- $\mathrm{irrigation\_runoff\_amount}$ and $\mathrm{irrigation\_evaploss\_amount}$ *which* are monitored values (mm) used to keep track of runoff and evaporation losses.
- $\mathrm{days\_since\_irrigation}$ which is a monitored value (days) that is reset on the day of irrigation and incremented daily.
- $\mathrm{FixedIrrigationAmount}$ which iss an input value representing a fixed irrigation input (mm). It can be read in directly from the input parameter file, or fetched from a predefined input time-series.
- $\mathrm{IrrigationBufferPeriod}$ which is an input parameter (days) defining the minimum number of days which must elapse between consecutive irrigations.
- SWD is the total soil water deficit (below field capacity and relative to wilting point) in mm.
- $\mathrm{IrrigationSWD}$ which is an input parameter represeting the “trigger point” for which to commence an irrigaiton. It represents the soil water deficit amount which must occur before an irrigaiton is viable.
- $\mathrm{EffectiveRain}$ which is the daily rainfall amount which may have uninfiltrated irrigation water added to it at the end of the irrigation calculations. This water is then availabe to the runoff calculations.
- $\mathrm{Irrigation\_amount}$ which is the actual amount of irrigation water applied (mm) on a day that is delivered to the field and includes infiltrated amounts and losses.
- $\mathrm{TargetAmountOptions}$ which is an enumerated input parmameter used to define how much water to “inject” into the soil layers. Possibilites include (defined below in Step 4):
    - $\mathrm{taFieldCapacity},$
    - $\mathrm{taSaturation},$
    - $\mathrm{taFixedAmount},$
    - $\mathrm{taDULplus25Percent},$
    - $\mathrm{taDULplus50Percent},$
    - $\mathrm{taDULplus75Percent},\ \mathrm{and}$
    - $\mathrm{taDULminus10PercentPAWC}.$
- $\mathrm{targetlayeramount}_{\mathrm{i}}$ which is the estimated amount of irrigation water which will be “injected” into the soil layer based on the user-defined setting of $\mathrm{TargetAmountOptions}.$
- $\mathrm{Layerdeficit}_{\mathrm{l}}$ which is the soil water deficit of the layer below field capacity and above wilting point (mm).

There are logical steps involved in triggering an irrigation event in the simulation model. These include:

- Step 1 – initialise the monitored variables $\mathrm{irrigation\_runoff\_amount}$ and $\mathrm{irrigation\_evaploss\_amount}$ to 0.
- Step 2 – check to see if this simulation has irrigation turned on.
- Step 3 – increment $\mathrm{days\_since\_irrigation}$ parameter:

$$days\_since\_irrigation = days\_since\_irrigation_{yesterday} + 1 \tag{5-1}$$

- Step 4–- check to see if irrigation conditions are met:
  - if using a “Sequence file” (array of irrigation dates and amounts):
    - check if today’s date is in a sequence list. If so, then extract irrigation amount from the input values:

$$FixedIrrigationAmount = \ value\_from\_list \tag{5-2}$$

    - set target amount type to $taFixedAmount$.
    - if all ok, **proceed with step 5**.
  - if using a fixed irrigation amount during crop growth stage, then:
    - check to see if crop is growing;
    - check if crop still requires irrigating;
    - check if days_since_irrigation is greater than $IrrigationBufferPeriod;$
    - check if SWD is greater than SWD for irrigation (testing $IrrigationSWD$);
    - check if $effectiveRain$ less than 0.01; and
    - if all ok, **proceed with Step 5**.
  - if using a “proportional” irrigation amount during crop growth stage:
    - check to see if crop is growing;
    - check if crop still requires irrigating;
    - check if $days\_since\_irrigation$ is greater than $IrrigationBufferPeriod;$
    - check if SWD is greater than SWD for irrigation;
    - check if $effectiveRain$ is less than 0.01; and
    - if all ok, **then proceed with Step 5**.
  - If using a fixed irrigation amount during nominated irrigation window, then:
    - check to see if today’s date is within “irrigation window”;
    - check to see if crop is growing;
    - check if crop still requires irrigating;
    - check if $days\_since\_irrigation$ is greater than $IrrigationBufferPeriod;$
    - check if SWD is greater than SWD for irrigation (testing $IrrigationSWD$);
    - check if $effectiveRain$ is less than 0.01; and
    - if all ok, **then proceed with Step 5**.
  - If using a “proportional” irrigation amount during nominated irrigation window:
    - check to see if today’s date is within “irrigation window”;
    - check to see if crop is growing;
    - check if crop still requires irrigating;
    - check if $days\_since\_irrigation$ is greater than $IrrigationBufferPeriod;$
    - check if SWD is greater than SWD for irrigation;
    - check if $effectiveRain$ less than 0.01; and
    - if all ok, **then proceed with Step 5**.

- Step 5 – calculate a target amount to apply:
  - if $TargetAmountOptions$ is equal to $taFieldCapacity:$

$$irrigation\_amount = swd \tag{5-3}$$

  - if $TargetAmountOptions$ is equal to $taSaturation:$

$$irrigation\_amount = satd \tag{5-4}$$

  - if TargetAmountOptions is equal to taFixedAmount:

$$irrigation\_amount = FixedIrrigationAmount \tag{5-5}$$

  - if TargetAmountOptions is equal to taDULplus25Percent:

$$irrigation\_amount = swd + (satd - swd) \times 0.25 \tag{5-6}$$

  - if TargetAmountOptions is equal to taDULplus50Percent:

$$irrigation\_amount = swd + (satd - swd) \times 0.50 \tag{5-7}$$

  - if TargetAmountOptions is equal to taDULplus75Percent:

$$irrigation\_amount = swd + (satd - swd) \times 0.75 \tag{5-8}$$

  - if TargetAmountOptions is equal to taDULminus10PercentPAWC:

$$irrigation\_amount = swd - pawc \times 0.1 \tag{5-9}$$

  - else:

$$irrigation\_amount = 0 \tag{5-10}$$

- Step 6–- if irrigation_amount is greater than 0, then attempt to irrigate:
  - Reset days_since_irrigation to 0.
  - If using a “Ring Tank”, check to see how much of this “irrigation_amount” can be extracted from the storage.
  - then try and extract any runoff water (see section 5.3).
  - then try and extract any evaporation/spray loss water (see section 5.4).
  - then “Push” this water through the individual soil layers. This ignores maximum drainage values for each layer. Instead, it distributes the water from the first layer, through to the final layer of the soil using what water is available (use a variable called “amount” and take away a “layer deficit” when iterating through each layer):

    - iterate through each soil layer I, and calculate a “target layer amount”:
      - if TargetAmountOptions is equal to taFieldCapacity:

$$targetlayeramount_i = DUL_i \tag{5-11}$$

  - if TargetAmountOptions is equal to taSaturation OR taFixedAmount (from sequence file):

$$targetlayeramount_i = SatLimit_i \tag{5-12}$$

  - if TargetAmountOptions is equal to taDULplus25Percent:

$$targetlayeramount_i = DUL_i + 0.25 \times (I \ - DUL_i) \tag{5-13}$$

  - if TargetAmountOptions is equal to taDULplus50Percent:

$$targetlayeramount_i = DUL_i + 0.50 \times (SatLimit_I \ - DUL_i) \tag{5-14}$$

  - if TargetAmountOptions is equal to taDULplus75Percent:

$$targetlayeramount_i = DUL_i + 0.75 \times (I \ - DUL_i) \tag{5-15}$$

  - if TargetAmountOptions is equal to taDULminus10Percent:

$$targetlayeramount_i = DUL_i - DUL_i \times 0.10 \tag{5-16}$$

- using this targetlayeramount$_i$, calculate a layer deficit:

$$Layerdeficit_i = targetlayeramount_i - PAW_i \tag{5-17}$$

- if the amount of applied irrigation water remaining (amount) is greater than the Layerdeficit$_i$, then:

$$SW_i = targetlayeramount_i \tag{5-18}$$

- else if not enough applied irrigation water remains (amount) to fill that layer deficit, then:

$$SW_i = SW_i + amount \tag{5-19}$$

- finally, recalculate “amount”:

$$amount = amount - Layerdeficit_i \tag{5-20}$$

- Then recalculate the total soil water deficit (swd):

$$swd = \sum_{i=1}^{i=layercount} (DUL_i - PAW_i) \tag{5-21}$$

- Then recalculate $sse1$:

$$sse1 = Max(0, sse1 - \mathrm{swd}) \tag{5-22}$$

- Then if any applied water is remaining (that did not get stored in the layers), add it to “$\mathrm{effective\_rainfall}$” so that it will be accounted for by runoff/drainage:

$$effective\_rainfall = effective\_rainfall + amount \tag{5-23}$$

5.3 Remove runoff from irrigation amount

The irrigation submodel allows the user to remove a runoff amount before inserting the irrigation water into the soil layers. This runoff is later added to the runoff component of the water balance. If the proportional option is chosen, then during the first irrigation of the season:

$$irrigation\_runoff = applied \times IrrigationRunoffProportion1/100.0 \tag{5-24}$$

During subsequent irrigations:

$$irrigation\_runoff = applied \times IrrigationRunoffProportion2/100.0 \tag{5-25}$$

where:

- $\mathrm{IrrigationRunoffProportion1}$ and $\mathrm{IrrigationRunoffProportion2}$ are defined in the input parameters.

If the sequence option is chosen, then $\mathrm{irrigation\_runoff}$ is assigned the value from the sequence file but is limited by the $\mathrm{applied}$ amount.

5.4 Remove evaporation from irrigation amount

The irrigation submodel also allows the user to remove an evaporation amount from the applied irrigation water before distributing water through the soil. This accounts for both surface water evaporation and potential spray drift. This evaporation amount is later added to the evaporation component of the water balance. If the proportional option is chosen, then:

$$\begin{aligned} irrigation\_evaporation \\ = applied \times IrrigationEvaporationProportion/100.0 \end{aligned} \tag{5-26}$$

where:

- $\mathrm{IrrigationEvaporationProportion}$ is defined in the input parameters.

6 Residue submodel (including tillage)

Crop residue calculations depend on the crop model used. The LAI model is the most complex submodel as it estimates residue decay over time and allows tillage operations to be simulated. Cover and Crop-Factor models do not estimate residue, rather they input this from the predefined residue cover.

6.1 LAI model residue calculations

The LAI residue and tillage submodel is comprised of three related components; residue decay through time, residue reduction by tillage; and a cover weight vs percent cover relationship. A daily balance of the weight of crop residue on the surface is maintained. Crop dry matter remaining after harvest is added to the residue pool. Residue incorporation during tillage operations and rates of residue decomposition are related to previous crop type and tillage implement using the functions developed by Sallaway, Lawson and Yule (1989). Percentage of the ground surface with residue cover is estimated from residue weight on a daily basis.

The residue submodel is a critical component within ***HowLeaky*** LAI model because it allows the model to quantify the effects of different land management practices. For example, changing a tillage implement will affect both surface cover and surface roughness which in turn affects runoff, soil evaporation and erosion. Changing crop types will produce varying amounts of residue with different levels of effectiveness which in turn affects hydrology and erosion. Maintaining a surface residue and surface roughness balance is a crucial component of any cropping systems model. Specifically, estimates of surface cover are used to modify the curve number parameter for runoff prediction, the potential evaporation rate in the soil evaporation algorithm and the amount of soil erosion. Tillage also creates varying amounts of surface roughness, dependent on tillage type, which affects the prediction of surface runoff.

There are two methodologies for calculating residue with the LAI model:

- ***PERFECT*** methodology; and
- Robinson methodology (undocumented).

6.1.1 *PERFECT* method for residue calculation

This method decays residue and calculates surface cover. Residue is decayed via Sallaway's functions (Sallaway et al., 1989). The residue decay submodel estimates the natural decay rate (weathering) of stubble after harvest. This model assumes an initial high residue decay rate of 15 kg/ha/day for 60 days after harvest followed by a lower rate of 3kg/ha/day. Note that residue will continue to decay through fallow and any subsequent crops. Decaying crop residue is redefined on a daily basis as follows:

- if in fallow and days since fallow is less than 60 days:

$$crop\_residue = Max(0, crop\_residue - 15) \tag{6-1}$$

- if in fallow and days since fallow is greater than or equal to 60 days:

$$crop\_residue = Max(0, crop\_residue - 3) \tag{6-2}$$

- else (if not in fallow):

$$crop\_residue = Max(0, crop\_residue - 15) \tag{6-3}$$

Factors for residue reduction by tillage are shown in Table 4.1 and were based on SOILOSS Rosewell and Edwards (1988), Sallaway et al. (1989), EPIC (Williams, 1983) and SWRRB (Williams, Nicks & Arnold, 1985). Residue weight is reduced by the appropriate percentage for the specified tillage implement. These factors are defined through "tillage parameter files" and can be changed by the user.

Table 2 – Default residue reductions and surface roughness ratios for different tillage implements

Tillage Implement	Residue reduction (%)	Roughness ratio
Stubble burnt	95	0.0
Disc Plough	60	1.0
Planter	50	0.0
Scarifier	40	0.7
Chisel Plough	35	0.6
Blade plough	20	0.3
Sweep plough	18	0.3
Rod Weeder	10	0.2
Herbicide	0	0.0

The weathering and tillage submodels modify residue weight. ***HowLeaky*** relates percent cover to residue weight using a generic form of the relationships developed by Sallaway et al. (1989). An asymptotic relationship residue weight and percent cover is assumed.

Then residue cover is calculated:

$$residue\_cover = MaximumResidueCover \times \left(1 - e^{-1\times\frac{crop\_residue}{1000}}\right) \tag{6-4}$$

6.1.2 Robinson method for residue calculation

This method accounts for rain over the last two days by calculating a "moisture index" (mi). However, this does not take into consideration irrigation in the previous days:

$$mi = \frac{4}{7} \times \left(\frac{Min(effective\_rain, 4)}{4} + \frac{Min(rain_{yesterday}, 4)}{8} + \frac{Min(rain_{daybeforeyesterday}, 4)}{16}\right) \tag{6-5}$$

Then calculate "temperature index" (ti):

$$ti = Min\left(\frac{temperature}{30}, 0\right) \tag{6-6}$$

A multiplier for decomposition is then calculated as the minimum of mi, ti and 1. It has been called $decompdays$ in the code (perhaps incorrectly), but will range between 0 and 1:

$$decompdays = Min(Min(mi, ti), 1) \tag{6-7}$$

Then crop residue is calculated as:

$$crop\_residue = Max\left(0, crop\_residue - crop\_residue \times \frac{DecompositionRate}{100} \times decompdays\right) \tag{6-8}$$

Residue cover is calculated as:

$$Residue\_cover = Min\left(1, \frac{crop_{residue}}{BiomassAtFullCover}\right) \tag{6-9}$$

7 Erosion submodel

Soil erosion is estimated on a daily basis using functions that relate soil erosion to runoff volume, surface and crop cover, rainfall erosivity, soil erodibility, management practice and topography (Freebairn & Wockner, 1986). This submodel predicts soil erosion for each day during a runoff event. Predictions of daily rates of erosion from these types of models may be in error (Littleboy et al., 1992a) because of the exclusion of rainfall intensity. However, this type of model is relatively accurate in predicting long-term average annual erosion (Littleboy et al., 1992a).

This submodel calculates sediment yield in tonnes/ha. Firstly, erosion_t_per_ha and sed_catchmod (***CatchMODS*** model compatible output) are initialized to zero. Next step is to calculate sediment concentration ($sediment\_conc$). If runoff is less than or equal to 1, then:

$$sediment\_conc = 0 \tag{7-1}$$

otherwise, calculation of sediment concentration (sediment_conc) involves first estimating cover (%). If there is no irrigation, then cover is calculated as:

$$cover = Min(100, (cover_{crop} + cover_{residue} \times (1 - cover_{crop})) \times 100) \tag{7-2}$$

In the ***HowLeaky*** computer code, there is an option for irrigation “cover effects”. Currently, this option does not appear in the user interface so there is no way to change this from the default values of “Canopy and Stubble". If this default option is activated, cover will be calculated via one of three options:

- irrigation cover effects = “Canopy and Stubble", use Equation 7-2.
- irrigation cover effects = "Stubble only":

$$cover = \mathrm{Min}(100.0\ (0 + cover_{residue} * (1 - 0)) * 100.0) \tag{7-3}$$

- irrigation cover effects = "No cover effects”:

$$cover = 0; \tag{7-4}$$

Then introduce a temporary variable conc (%) defined as the percentage of sediment concentration, which needs to be used to calculate erosion. Then If cover is less than 50%:

$$conc = 16.52 - 0.46 \times cover + 0.0031 \times cover^2 \tag{7-5}$$

else if cover is greater than or equal to 50:

$$conc = -0.0254 \times cover + 2.54 \tag{7-6}$$

Then:

$$conc = \mathrm{Max}(0, conc) \tag{7-7}$$

Then to calculate erosion and sediment:

$$erosion\_t\_per\_ha = \frac{conc \times USLE\_ls \times USLE\_k \times USLE\_p \times runoff}{10} \tag{7-8}$$

where the USLE parameters are from the Universal Soil Loss Equation (USLE, Renard, et al. 1993) representing:

- $USLE\_ls$ as the slope factor (see Appendix A12.5);
- $USLE\_k$ as the soil erodibility factor. It defines the inherent susceptibility of a soil to erosion per unit of rainfall erosivity and is defined for set cover and crop condition; and
- $USLE\_p$ known as the practice factor defining the effects of conservation practices other than those related to cover and cropping/soil water use practices.

When runoff occurs, calculate the sediment concentration:

$$sediment\_conc = \frac{erosion\_t\_per\_ha \times 100.0}{runoff} \times SedDelivRatio \tag{7-9}$$

where:

- $SedDelivRatio$ is the sediment delivery ratio (unitless).

An additional output $sed\_catchmod$ is also calculated to compare with outputs from the ***CatchMODs*** (https://fennerschool.anu.edu.au/research/products/catchmods) model, which ignores the $USLE\_ls$ factor:

$$sed\_catchmod = \frac{conc \times USLE\_k \times USLE\_p \times runoff}{10} \tag{7-10}$$

Keep track of the peak sediment concentration by checking if $sediment\_conc > peakSedConc$, then:

$$peakSedConc = sediment\_conc \tag{7-11}$$

Also, keep track of the cumulative peak sediment concentration, so that “event averages” can be worked out later on:

$$cumSedConc = cumSedConc + peakSedConc \tag{7-12}$$

Finally, calculate offsite sediment delivery:

$$offsite\_sed\_delivery = erosion\_t\_per\_ha \times SedDelivRatio \tag{7-13}$$

8 Pesticide submodel

The pesticide submodel incorporated into ***HowLeaky*** tracks dissipation of pesticides in the soil, crop stubble and vegetation and estimates pesticide concentrations in runoff partitioned between soluble and sediment bound phases. Equations implemented in the pesticide submodel have been adapted from CREAMS/GLEAMS (Leonard et al., 1987) and have been described by Rattray, Freebairn, McClymont, Owens and Robinson (2004) and Shaw et al. (2011) with new processes added for pesticides on the crop canopy and residue pools. Adaptations to the model have been based on experimental work conducted in Australia (Silburn, 2003).

Note that there are plans to upgrade the logic and operation of this model to better deal with wash-off and degradation from vegetation and stubble. Currently, as is described in this documentation, pesticide applied to vegetation and/or stubble will continue to degrade at a daily rate until a rainfall event of 5mm or greater occurs, after which, some of the pesticide is washed off into the soil. The remaining pesticide mass disappears altogether from the calculations (perhaps absorbed). When this was developed, there was little documentation and measured data available to help establish these relationships.

The model in its current form can estimate:

- applied pesticide on vegetation (g/ha);
- applied pesticide on stubble (g/ha);
- applied pesticide on soil (g/ha);
- pesticide on vegetation (g/ha);
- pesticide on stubble (g/ha);
- pesticide in the soil (g/ha);
- pesticide soil concentration (mg/kg);
- pesticide sediment phase concentration (mg/kg);
- pesticide water phase concentration (ug/L);
- pesticide runoff concentration (water+sediment) (ug/L) ;
- sediment delivered (g/L);
- pesticide lost in runoff water (g/ha);
- pesticide lost in runoff sediment (g/ha);
- total pesticide lost in runoff (g/ha);
- pesticide lost in leaching (g/ha), and
- pesticide losses as percent of last input (%).

Setting up the pesticide submodel is more detailed then the other submodels in ***HowLeaky***. The full set of pesticide input parameters is described in Appendix 6. Inputs require the user to first define a method for scheduling the pesticide applications. Precise scheduling is achieved by defining a single reoccurring annual application date or through a sequence of predefined historical dates and rates. Conditional scheduling can be achieved through specifying either a target number of growing degree days for a crop, a number of days after sowing, or a number of days since the start of a fallow. ***HowLeaky*** allows users to define an initial application rate, and then a different rate for subsequent applications.

The user must then describe where the pesticide is being applied, that is: above the canopy; below the canopy and above the mulch; or direct to the soil. Furthermore, to complete the application description, the model requires inputs on the product application rate (kg or L /ha), concentration of the active ingredient (g/L), the application efficiency and coverage (band-spraying percentage).

The half-life of the pesticide (in days) differs for the different positions of canopy, stubble and soil. Depending on where the pesticide is applied to the crop, the half-life and associated reference temperature must be specified for each position. To assess decomposition, the “Degradation Activation Energy (J/mol)” is required to define the energetic threshold for thermal decomposition reactions. Losses are defined through specification of cover wash-off fraction, mixing layer thickness (for defining concentrations), sorption coefficient (for binding to soil/sediment) and extraction coefficient (for runoff). Finally, a critical pesticide concentration (ug/L) for the runoff water is required to assess damaging conditions.

In operation, the model sequentially calculates pesticide degradation on vegetation, stubble and in the soil, before updating runoff concentrations and calculating runoff and leaching losses. The order of operations is:

- check/update days since application;
- check/apply new pesticides ;
- calculate degrading pesticide on vegetation;
- calculate degrading pesticide on stubble;
- calculate degrading pesticide in soil;
- calculate pesticide runoff concentrations;
- calculate pesticide losses;
- calculate pesticide “days above critical”; and
- update pesticide summary values.

8.1 Check/Apply new pesticides

The user has a range of options via the interface to trigger pesticide applications. This includes scheduling pesticides applications based on:

- “Fixed date”:
  - a reoccurring date each year.
- “From sequence file”:
  - using fixed sequence of application dates.
- “Growing degree days”:
  - initially compares crop $heat\_units$ with $PestTriggerGGDFirst$*; and*
  - subsequently, compares crop $heat\_units$ with $PestTriggerGGDFirst + PestTriggerGGDSubsequent \times applicationindex.$
- “Days after sowing”:
  - initially compares crop $days\_since\_planting$ with $PestTriggerDaysFirst$*; and*
  - subsequently, compares crop $days\_since\_planting$ with $PestTriggerDaysFirst + PestTriggerDaysSubsequent \times applicationindex.$
- “Days since fallow”:
  - initially compares crop $days\_since\_harvest$ with $PestTriggerDaysFirst$*; and*
  - subsequently, compares $crop\ days\_since\_harvest$ with $PestTriggerDaysFirst + PestTriggerDaysSubsequent \times applicationindex$

If any of these events are true, then:

$$CurrentProductRate = ProductRate \tag{8-1}$$

8.2 Apply pesticide

The total amount of pesticide applied (g/ha) can be calculated directly from the input parameters:

$$pest\_application_{total} = IngredConcentration \times CurrentProductRate \times \frac{PesticideEfficiency}{100} \times \frac{BandSpraying}{100} \tag{8-2}$$

where:

- $IngredConcentration$ is an input parameter representing the concentration of the pesticide active ingredient (for example, glyphosate) in the applied product (for example, Roundup) in g/L;
- $CurrentProductRate$ is assigned from the input parameters representing the amount of pesticide applied (L/ha). There are two values defined in the input parameters for this: one for the first application of the season; and one for subsequent applications;
- $PesticideEfficiency$ is an input parameter representing the percent of total applied pesticide that is retained in the paddock (on the vegetation, stubble or soil) immediately following an application; and,
- $BandSpraying$ is an input parameter representing the percent area of a paddock to which a pesticide is applied.

As part of setting up the pesticide inputs, the user can apply pesticide to combinations of the vegetation layer, the stubble layer or the soil. We are then able to work out how much of the application is applied to each component. If application position is to the vegetation layer, the amount applied to the vegetation layer (g/ha) is:

$$pest\_application_{veg} = pest\_application_{total} \times crop\_cover \tag{8-3}$$

Else:

$$pest\_application_{veg} = 0 \tag{8-4}$$

If the application position is to either the vegetation layer or the stubble layer:

$$stubble\_cover = (1 - crop\_cover) \times total\_residue\_cover \tag{8-5}$$

$$pest\_application_{stubble} = pest\_application_{total} \times stubble\_cover \tag{8-6}$$

Else:

$$pest\_application_{stubble} = 0 \tag{8-7}$$

Finally, regardless of the application position, the amount applied to the soil is then calculated as:

$$\begin{aligned} pest\_application_{soil} \\ &= pest\_application_{total} - pest\_application_{veg} \\ &- pest\_application_{stubble} \end{aligned} \tag{8-8}$$

A counter in maintained in the code to keep track of how many applications occur.

8.3 Calculate pesticide mass-balance on vegetation

When pesticide is applied to the vegetation layer, degradation of the pesticide mass ($\mathrm{pest\_mass_{veg}}$) occurs on a daily basis (assuming a first order degradation rate) up until at least 5mm or rainfall is received, after which, some of the pesticide is washed off, and the following day, all remaining pesticide mass is reset to zero.

Calculations start by assigning key constants including the universal gas constant (UGC), the half-life reference temperature for vegetation in degrees Kelvin ($\mathrm{T_{Ref\_veg(kelvin)}}$) and the average air temperature for the day in degrees Kelvin ($\mathrm{T_{air(kelvin)}}$):

$$UGC = 8.314472 \tag{8-9}$$

$$T_{Ref\_veg(kelvin)} = HalfLifeRefTempVeg + 273.15 \tag{8-10}$$

$$T_{Air(kelvin)} = \frac{\mathrm{T}_{max} + \mathrm{T}_{min}}{2} + 273.15 \tag{8-11}$$

Then the half-life of pesticide (days) on vegetation ($\mathrm{HalfLife^{*}_{Veg}}$) is calculated, along with the degradation rate ($\mathrm{DegRate_{Veg}}$). The half-life is re-calculated daily based on the average air temperature ($\mathrm{T_{Air(kelvin)}}$) and a reference half-life ($\mathrm{HalfLife_{Veg}}$) at a known temp ($\mathrm{T_{Ref\_veg(kelvin)}}$) assuming an Arrhenius relationship (Walker, Helwig & Jacobsen, 1997).

$$HalfLife^{*}_{Veg} = HalfLife_{Veg} \times e^{\left(\frac{DegActEnergy}{UGC} \times \left(\frac{1}{T_{air(kelvin)}} - \frac{1}{T_{Ref\_veg(kelvin)}}\right)\right)} \tag{8-12}$$

$$DegRate_{Veg} = e^{-\left(\frac{0.693}{HalfLife^{*}_{Veg}}\right)} \tag{8-13}$$

On any day (with no significant rainfall), the pesticide mass on the vegetation is recalculated by multiplying the previous day's mass by the degradation rate, and by adding on any new pesticide amounts that may have been applied that day.

$$pest\_mass_{veg} = pest\_mass_{veg} \times DegRate_{Veg} + pest\_application_{veg} \tag{8-14}$$

Wash-off of pesticide to the soil may occur from the vegetation foliage and is triggered by at least 5mm of rainfall on a day. The amount remaining after wash-off to the soil is determined by the wash-off coefficient (fCW). Therefore, if today's rainfall is greater than or equal to 5 mm (we have assumed this is sufficient to wash off part of pesticide off the vegetation) and yesterday was "dry", we then need to adjust the mass value.

Therefore, if yesterday was dry (<5mm) and today has had significant rainfall (≥5mm):

$$pest\_mass_{veg} \ = pest\_mass_{veg} \times (1 - fCW) \tag{8-15}$$

However, if has been significant rainfall (≥5mm) yesterday, regardless of the rainfall today, the methodology assumes that it can now consider all pesticide mass on the vegetation to be lost:

$$pest\_mass_{veg} = 0 \tag{8-16}$$

8.4 Calculate pesticide mass-balance on stubble

The pesticide mass balance on the stubble is calculated next (if applicable). A similar methodology to that applied to pesticide on the vegetation is used, although the degradation rates and half-life may differ based on the input values provided. Pesticide degrades over time on the stubble according to its half-life and current air temperature. Calculations start by assigning key constants before calculating a degradation rate ($\mathrm{DegRate}_{\mathrm{Stub}}$).

$$T_{Ref\_stub(kelvin)} = HalfLifeRefTempStubble + 273.15 \tag{8-17}$$

Then the half-life of pesticide on stubble $\mathrm{HalfLife}^*_{\mathrm{Stub}}$ is calculated from the previous days estimate ($\mathrm{HalfLife}_{\mathrm{stub}}$), along with the degradation rate:

$$HalfLife^*_{Stub} = HalfLife_{stub} \times e^{\left(\frac{DegActEnergy}{UGC} \times \left(\frac{1}{T_{air(kelvin)}} - \frac{1}{T_{Ref\_stub(kelvin)}}\right)\right)} \tag{8-18}$$

$$DegRate_{Stub} = e^{-\frac{0.693}{HalfLife^*_{Stub}}} \tag{8-19}$$

On any day (with no significant rainfall), the pesticide mass on the stubble is recalculated by multiplying the previous day's mass by the degradation rate, and by adding on any new pesticide amounts that may have been applied that day.

$$pest\_mass_{stub} = pest\_mass_{stub} \times DegRate_{stub} + pest\_application_{stub} \tag{8-20}$$

Then consider wash-off effects on the stubble in the same way that was done with the vegetation. If yesterday's rainfall is less than 5 mm and more than 5mm was received today, then the pesticide mass is adjusted via a wash-off function:

$$pest\_mass_{stub} = pest\_mass_{stub} \times (1 - fCW) \tag{8-21}$$

However, if yesterday had a significant rainfall (≥5mm) event, regardless of the rainfall today, the methodology assumes that it can now consider all pesticide mass on the stubble to be lost:

$$pest\_mass_{stub} = 0 \tag{8-22}$$

8.5 Calculate pesticide mass-balance in the soil

Next, assess the mass balance in the soil. This could include washed-off portions of the pesticide from the vegetation and stubble. Like the previous calculations, pesticide in the soil degrades over time according to its half-life and current air temperature. Calculations start by assigning key constants before calculating a degradation rate ($\mathrm{DegRate}_{\mathrm{soil}}$) for the soil:

$$T_{Ref\_soil(kelvin)} = HalfLifeRefTempSoil + 273.15 \tag{8-23}$$

Then the half-life of pesticide in the soil is calculated:

$$HalfLife^{*}_{soil} = HalfLife_{soil} \times e^{\left(\frac{DegActEnergy}{UGC} \times \left(\frac{1}{T_{air(kelvin)}} - \frac{1}{T_{Ref\_soil(kelvin)}}\right)\right)} \tag{8-24}$$

Then the degradation rate on soil is calculated:

$$DegRate_{soil} = e^{-\left(\frac{0.693}{HalfLife^{*}_{soil}}\right)} \tag{8-25}$$

The mass in the soil can then be estimated by a volume balance:

$$\begin{aligned} pest\_mass_{soil} \ = \ & pest\_mass_{soil} \times DegRate_{soil} + \ pest\_applied_{soil} \\ & - pest\_loss_{leaching} - pest\_loss_{runoff\_total} \end{aligned} \tag{8-26}$$

where:

- $\mathrm{pest\_loss}_{\mathrm{leaching}}$ and $\mathrm{pest\_loss}_{\mathrm{runoff\_total}}$ are losses calculated in Section 8.7.

If today’s rainfall was enough to cause wash-off from the vegetation and stubble, then adjust the pesticide mass in the soil for these additional components:

$$pest\_mass_{soil} \ = \ pest\_mass_{soil} + (pest\_mass_{stub} + pest\_mass_{veg}) \times fCW \tag{8-27}$$

Finally, calculate the pesticide concentration (mg/kg) in the soil:

$$pest\_conc_{soil} = \frac{pest\_mass_{soil}}{BulkDensity_0 \times MixLayerThickness \times 10} \tag{8-28}$$

Then to calculate the concentration in the soil after leaching, first calculate the porosity of the soil:

$$porosity = 1 - \frac{BulkDensity_0}{2.65} \tag{8-29}$$

To work out how much soil water is available for mixing with the pesticide:

$$availwaterstorageinmixing = (DUL_0 - PAW_0) \times \frac{MixLayerThickness}{depth_1} \tag{8-30}$$

The total water available for leaching the pesticide is:

$$infilt = rain - runoff - \ availwaterstorageinmixing \tag{8-31}$$

Lastly, the final concentration after leaching is:

$$pest\_conc_{\ soil\_after\_leach} = \ pest\_conc_{soil} \times e^{-\frac{infilt}{MixLayerThickness*(SorptionCoefficient \times BulkDensity_0 + porosity)}} \tag{8-32}$$

8.6 Calculate pesticide concentration in runoff

To calculate the concentration of pesticide lost in runoff (water + sediment), first calculate a coefficient sorpBYext which is used to combine extraction and sorption coefficients:

$$sorpBYext = SorptionCoefficient \times ExtractionCoefficient \tag{8-33}$$

where:

- SorptionCoefficient is defined in the input parameters and represents the amount of pesticide bound to soil/sediment versus the amount in the water phase (unitless); and,
- ExtractionCoefficient is defined in the input parameters and represents the fraction of pesticide present in the soil that will be extracted into runoff. This include pesticide present in runoff in both the sorbed and dissolved phases (unitless).

Then the concentration in the runoff water (ug/L) is:

$$pest\_conc_{runoff\_water} = pest\_conc_{soil\_after\_leach} \times \frac{ExtractionCoefficient}{1 + sorpBYext} \times 1000 \tag{8-34}$$

The concentration in the runoff sediment (mg/kg) is:

$$pest\_conc_{runoff\_sed} = pest\_conc_{soil\_after\_leach} \times \frac{sorpBYext}{1 + sorpBYext} \tag{8-35}$$

Finally, the total pest concentration in runoff (ug/L) combines that in the water and that attaches to sediment:

$$pest\_conc_{runoff\_total} = pest\_conc_{runoff\_water} + pest\_conc_{runoff\_sed} \times sediment\_conc \qquad \text{8-36}$$

8.7 Calculate pesticide losses

To calculate the total pesticide losses in the runoff water (g/ha), multiply the concentration in the runoff by the amount of runoff:

$$pest\_loss_{runoff\_water} = pest\_conc_{runoff\_water} \times runoff \times 0.01 \qquad \text{8-37}$$

Similarly, calculate the total losses attached to sediment (g/ha) by multiplying the concentration attached to the sediment by the amount of erosion (factoring in the delivery ratio):

$$pest\_loss_{runoff\_sed} = pest\_conc_{runoff\_sed} \times erosion\_t\_per\_ha \times SedDelivRatio \qquad \text{8-38}$$

where:

- SedDelivRatio is an input parameter defined in the soil parameters file representing the sediment concentration in runoff water from the total eroded amount.

Then total losses (g/ha) equals the summation of the previous two components:

$$pest\_loss_{runoff\_total} = pest\_loss_{runoff\_water} + pest\_loss_{runoff\_sed} \qquad \text{8-39}$$

To calculate total losses in leaching water (g/ha), update the volume balance in the soil by working out the concentration in the water removed, and adjusting for density and mixing layer thickness:

$$pest\_loss_{leaching} = \left(pest_{conc\,soil} - pest_{conc\,soil_{after_{leach}}}\right) \times BulkDensity\_0 \times MixLayerThickness/10 \qquad \text{8-40}$$

Finally, calculate the total pesticide loss as a percentage of pesticide applied:

$$percent\_pest\_loss = \frac{pest\_loss_{runoff\_total} + pest\_loss_{leaching}}{pest\_application} \times 100 \qquad \text{8-41}$$

9 Phosphorus submodel

The phosphorus model was first introduced into ***HowLeaky*** in 2006 and is described by Robinson, Rattray, Freebairn, Silburn, and McClymont (2007). It was introduced to support the modelling work in the Reef Plan program (www.reefplan.qld.gov.au) to address the issue of nutrient impact on the health and future of the Great Barrier Reef.

The ***HowLeaky*** model is one of a few biophysical models that represent agricultural management, biophysical conditions and Phosphorus (P) exports. However, the predictive power of the early model was modest, especially over short periods (for example, individual days). To improve the predictive power of the model, several modifications[4] were introduced in 2009, including:

- additional empirical functions for estimating the enrichment of total P in sediment;
- additional functions for estimating concentration of soluble P in runoff (mg P/L);
- soil adsorption of P (P buffering), which affects the soluble P concentration in runoff, is now estimated from the widely available phosphorus buffering index test (PBI) rather than phosphorus buffering capacity (PBC).

The model in its current form can estimate particulate and dissolved P loads and concentrations, as well as two ***CatchMODS*** (https://fennerschool.anu.edu.au/research/products/catchmods) compatible outputs, including:

- particulate concentrations (mg/L).
- dissolved concentrations (mg/L).
- bioavailable particulate P concentrations (mg/L).
- bioavailable dissolved P concentrations (mg/L).
- total P concentrations (mg/L).
- particulate P export (kg/ha).
- dissolved export (kg/ha).
- bioavailable particulate P export (kg/ha).
- total bioavailable export (kg/ha).
- total phosphorus export (kg/ha).
- CKQ (t/ha) – CatchMODS compatible sediment output:

$$CKQ = conc \times USLE\_K \times USLE\_P \times runoff/10.0 \tag{9-1}$$

- $PPHLC$ (kg/ha) – CatchMODS compatible particulate P output:

$$PPHLC = \frac{Phos\_Export\_Partic\_kg\_per\_ha}{SedDelRatio \times USLE\_LS} \tag{9-2}$$

In practice, the model sequentially calculates dissolved, particulate and total phosphorus before calculating bioavailable phosphorus. This occurs only when runoff is greater than zero. The order of operations is:

- calculate Dissolved Phosphorus;
- calculate Particulate Phosphorus;
- calculate Total Phosphorus;
- calculate Bioavailable Particulate Phosphorus;
- calculate Bioavailable Phosphorus; and

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[4] Some of these options have now been removed .

- test Maximum Phosphorus Concentrations.

Input parameters include options for the dissolved P methodology (“Vic DPI” or “QLD Reef”), total P concentration (mg/kg), Colwell P (mg/kg), phosphorus buffering index and two enrichment ratio options (“Constant Ratio” or “Empirical Clay function”). A detailed description of the input parameters is provided in Appendix 7. The model does not take into account any P inputs, other than those that may have affected the soil total P and Colwell P status.

Note, the notation used in the following equations tends to be longer than other equations described in this document and often has units in the parameter names. It is the same notation as used in the computer code and is helpful in clarifying the units and unit conversions being used.

9.1.1 Calculate phosphorus enrichment ratio

Central to the Phosphorus model is the estimation of the P enrichment ratio, which is used to account for the preferential transport of P-rich fine material from hillslopes. The P enrichment ratio describes the enrichment of soil P (mg/kg) into sediment suspended in runoff (mg/kg). In ***HowLeaky*** there are two alternative methods for estimating the ratio:

- Option 1 - “Constant Ratio”: is a fixed ratio obtained directly from the user. This method is simple and is especially suitable if the ratio has been measured (Sharpley, 2007). In general, soils with sandy or organic surface layers or P stratified in the surface are likely to have higher enrichment ratios than clay soils and uniform soils.
- Option 2 - “Empirical Clay function”: is an empirical function based on the clay content (%) of the topsoil (Equation 9-3):

$$EnrichmentRatio = Min(10, Max(1.15 - 0.33 \times ClayPercentage)) \quad \text{9-3}$$

where $ClayPercentage$ is the percentage clay in the top-soil. The range of the function is limited to 1 ($ClayPercentage > 45$) to 10 ($ClayPercentage < 15$).

This method is based on data from soils in Queensland that ranged from 26 to 65% clay, and so is best suited to clay soils (personal communication, B. Robinson, 2009). The enrichment ratios are high (5.1) for soils less than 30% clay. This method is based on limited data.

9.2 Calculate dissolved phosphorus

There are currently two alternative methods of estimating dissolved reactive P concentrations (mg/L) in runoff (DRP, also known as filterable reactive P):

- Option 1 (labelled “VIC DPI”) is a suite of three functions, based on large datasets, that predict DRP from the degree of saturation of the P adsorption capacity of the soil; and
- Option 2 (labelled “QLD REEF”) is based on dissolved P (DP, mg/L) runoff data from pastures (Dougherty, Burkitt, Milham & Harvey, 2010) and estimating DRP as a proportion of DP.

Both methods involve calculating “P max sorption coefficient”, “P enrichment ratio” and the “P saturation index” before estimating the dissolved concentration using one of two relationships determined by the magnitude of the “P saturation index”.

“P saturation index” represents available P, as measured by the Colwell (1963) method, as a percentage of the soil P sorption capacity (mg/kg). P saturation is a simple notion that can be difficult to estimate and employ. “P max sorption” was previously estimated in ***HowLeaky*** from soil phosphorus buffer capacity (PBC), described by Ozanne and Shaw (1968) and the adsorption equation of Langmuir (1916). However, the method is laborious, and consequently, not widely adopted. ***HowLeaky*** now estimates P max sorption from PBI – a widely measured, single point measure of P buffering (Burkitt, Moody, Gourley, & Hannah, 2002).

9.2.1 Option 1 – labelled “VIC DPI”

The Victorian DPI method uses an exponential equation to calculate $p\_max\_sorption$:

$$p\_max\_sorption = 1447 \times (1 - e^{-0.001 * PBI}) \tag{9-4}$$

where:

- PBI is the phosphorus buffering index as defined in the input parameters.

Then:

$$p\_enrich = CalculatePhosphorusEnrichmentRatio() \tag{9-5}$$

where:

- p_enrich is calculated using either the “Constant Ratio” or “Empirical Clay function” methodology as described in the previous section.

Then the phosphorus saturation index is calculated as:

$$phos\_saturation\_index = \frac{ColwellP \times p\_enrich}{p\_max\_sorption} \times 100 \tag{9-6}$$

where:

- $ColwellP$ (mg/kg) is the amount of easily extracted P in the topsoil (0-10 cm, extracted with bicarbonate).

Now calculate the dissolved reactive P concentrations (mg/L) in runoff which is dependent on the value of the phosphorus saturation index. If $phos\_saturation\_index$ is less than 5:

$$Phos\_Conc\_Dissolve\_mg\_per\_L = \frac{10 \times phos\_saturation\_index}{1000} \tag{9-7}$$

else if $phos\_saturation\_index$ is greater than or equal to 5:

$$Phos\_Conc\_Dissolve\_mg\_per\_L = \frac{-100.0 + 30 \times phos\_saturation\_index}{1000} \tag{9-8}$$

Finally, calculate the total dissolved amount exported in the runoff:

$$Phos\_Export\_Dissolve\_kg\_per\_ha = \frac{Phos\_Conc\_Dissolve\_mg\_per\_L}{1000000} \times runoff \times 10000 \tag{9-9}$$

9.2.2 Option 2- (labelled “QLD REEF”)

The Queensland Reef methodology uses a quadratic equation to calculate p_max_sorption:

$$p\_max\_sorption = Max(50,\quad 5.84 \times PBI - 0.0096 \times PBI^2) \tag{9-10}$$

Then the p_enrich and phos_saturation_index values are calculated the same way that they were in Equations 9-5 and 9-6.

If phos_saturation_index is less than 10:

$$Phos\_Conc\_Dissolve\_mg\_per\_L \;=\; 7.5 \times \frac{phos\_saturation\_index}{1000} \tag{9-11}$$

otherwise:

$$Phos\_Conc\_Dissolve\_mg\_per\_L \;=\; \frac{-200.0 \;+\; 27.5 \times phos\_saturation\_index}{1000} \tag{9-12}$$

Finally:

$$Phos\_Export\_Dissolve\_kg\_per\_ha = \frac{Phos\_Conc\_Dissolve\_mg\_per\_L}{1000000} \times runoff \times 10000 \tag{9-13}$$

9.3 Calculate particulate phosphorus

Calculations start by calculating the phosphorus enrichment ratio (p_enrich) from Equation 9-5. Then to calculate the P sediment concentration in the runoff, first convert the erosion value from t/ha to g/ha and runoff from mm to L/ha. Then the division yields g/L of sediment:

$$p\_sed\_conc\_g\_per\_l = \frac{erosion\_t\_per\_ha \;\times\; 1000000.0}{(runoff \;\times\; 10000.0)} \;*\; SedDelivRatio \tag{9-14}$$

Then convert sediment concentration from g/L to mg/L and total P concentration from mg/kg to g/g:

$$Phos\_Conc\_Partic\_mg\_per\_L = \frac{p\_sed\_conc\_g\_per\_l \;\times\; 1000.0 \;\times\; TotalPConc}{1000000} \;\times\; p\_enrich \tag{9-15}$$

where:

- TotalPConc is the total P content of the soil (mg/kg) as defined in the input parameters.

Finally, calculate the particulate P export (kg/ha):

$$Phos\_Export\_Partic\_kg\_per\_ha = \frac{Phos\_Conc\_Partic\_mg\_per\_L}{1000000} \times runoff \times\; 10000 \tag{9-16}$$

9.4 Calculate total phosphorus

Total phosphorus concentrations and loads can then be calculated by adding the dissolved and particulate components:

$$\begin{aligned}Phos\_Conc\_Total\_mg\_per\_L \\ = Phos\_Conc\_Dissolve\_mg\_per\_L \\ + Phos\_Conc\_Partic\_mg\_per\_L\end{aligned} \tag{9-17}$$

and:

$$\begin{aligned}Phos\_Export\_Total\_kg\_per\_h \\ = Phos\_Export\_Dissolve\_kg\_per\_ha \\ + Phos\_Export\_Partic\_kg\_per\_ha\end{aligned} \tag{9-18}$$

9.5 Calculate bioavailable particulate phosphorus

Calculation of the bioavailable particulate P involves calculating:

$$pA = \frac{ColwellP \times 1.2}{TotalPConc} \tag{9-19}$$

The bioavailable particulate P concentration is then equal to:

$$Phos\_Conc\_BioPartic\_mg\_per\_L = Phos\_Conc\_Partic\_mg\_per\_L \times pA \tag{9-20}$$

Then the total bioavailable particulate P is calculated as:

$$Phos\_Export\_BioPartic\_kg\_per\_ha = Phos\_Export\_Partic\_kg\_per\_ha \times pA \tag{9-21}$$

9.6 Calculate bioavailable phosphorus

To calculate bioavailable P, we first calculation the concentration:

$$\begin{aligned}Phos\_Conc\_Bio\_mg\_per\_L \\ = 0.8 \times Phos\_Conc\_Dissolve\_mg\_per\_L \\ + Phos\_Conc\_BioPartic\_mg\_per\_L\end{aligned} \tag{9-22}$$

Then total bioavailable P loading is:

$$\begin{aligned}Phos\_Export\_Bio\_kg\_per\_ha \\ = 0.8 \times Phos\_Export\_Dissolve\_kg\_per\_ha \\ + Phos\_Export\_BioPartic\_kg\_per\_ha\end{aligned} \tag{9-23}$$

10 Nitrate-N submodel

The Nitrate-N submodel was introduced in 2014 by the Victorian Department of Primary Industries to post-process ***DairyMod*** (http://imj.com.au/dairymod/) outputs in ***HowLeaky***. It contains a subset of three separate models for calculating: dissolved Nitrate-N in runoff; dissolved Nitrate-N in leaching; and particulate Nitrate-N in runoff. These models do **not** employ a nitrate "Volume-Balance" and they do **not** "route" nitrate through the soil. Instead, they represent a simplified approach whereby (in most cases) a nitrate concentration profile in the soil through time is defined and responds to runoff and drainage events by estimating what Nitrate would be removed during those events. The exception to this rule is in estimating dissolved inorganic nitrogen in runoff using the method of Rattray (Rattray, Shaw & Silburn, 2016) or Fraser (Fraser, Rohde & Silburn, 2017), which look at runoff concentrations after a fertiliser application.

Note that nitrate concentrations for the soil profile can be obtained from experiments or expert knowledge, while the soil nitrate concentration in the deepest soil layer can be informed by other nitrogen biophysical models (e.g. ***DairyMod***).

Output from the model include:

- Dissolved Nitrate-N in Runoff (mg/L)[5];
- Nitrate-N Runoff Load (kg/ha);
- Dissolved Nitrate-N in Leaching (mg/L);
- Nitrate-N Leaching Load (kg/ha);
- Particulate Nitrate-N in Runoff (kg/ha);
- PNHLC (kg/ha) – CatchMODS specific Particulate Nitrate-N output;
- Nitrate-N Store (top layer) (kg/ha);
- Nitrate-N Store (bottom layer) (kg/ha); and
- Total Nitrate-N Store (top layer) (kg/ha).

The three nitrate submodels represent three independent sets of calculations. These are enabled by the user via the nitrate settings in the user interface. One or more of these settings can be enabled (none of them are compulsory) by selecting from a range of options in each category. These options include:

- **Estimate dissolved Nitrate-N in runoff**. Options include:
  - "None".
  - "Imported time-series":
    - set depth of top layer (for Nitrate-N movement);
    - define k (soil water/runoff mixing factor);
    - define cv (soil water/runoff curvature factor);
    - define alpha (dissolved N calibration factor);
    - select source data-file (can be attached to project or loaded via the inputs);
    - select which time-series in the data-file which represents "Nitrate-N Store in top layer (kg/ha)"; and
    - define a scaling factor for the imported time-series (for calibration).
  - "User-defined profile":
    - uses the same parameters defined in "Imported time-series", except that the time-series is not read in from a datafile, but from an annual profile of amounts (Nitrate-N stored in the top layer [kg/ha] and dates [Julian day].
  - "Rattray empirical function" (developed from P2R banana DIN runoff data; Rattray et al. 2016):
    - Define Power Fit Alpha value;
    - Define Power Fit Beta value;

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[5] The methods of Rattray and Fraser calculates dissolved inorganic nitrogen (DIN) which includes N03 N plus NH4 N.

        - Define maximum disolved inorganic nitrogen runoff concentration (mg/L);
        - Define minimum disolved inorganic nitrogen runoff concentration (mg/L);
        - Define fertiliser application sequence of rates and dates (dd/mm/yyyy) format; and
        - **REQUIRES TIME-SERIES** to run (see notes below).
    - "Frazer empirical function" (developed from P2R sugar cane DIN runoff data, Fraser et al. 2017):
        - define daily loss proportion (0-1);
        - define rainfall loss-DIN loss per mm of effective rain/irrigation (mg/L);
        - define low limit DIN concentration (approach rainfall) (mg/L);
        - define fertiliser application sequence of rates and dates (dd/mm/yyyy) format; and
        - **REQUIRES TIME-SERIES** to run (see notes below).
- **Estimate dissolved Nitrate-N in leaching**. Options include:
    - None.
    - Imported time-series:
        - define the depth of the bottom layer (for N movement).
        - define a nitrate leaching efficiency (0-1).
        - select source data-file (can be attached to project or loaded via the inputs):
            - select which time-series in the data-file represents "Nitrate-N Store in bottom layer (kg/ha)".
        - define a scaling factor for the imported time-series (for calibration).
    - User-defined profile:
        - uses the same parameters defined in "Imported time-series", except that the time-series is not read in from a datafile, but from an annual profile of amounts (Nitrate-N stored in the bottom layer [kg/ha] and dates [Julian day]).
- **Estimate particulate Nitrate-N in runoff**. Options include:
    - None.
    - Import time-series:
        - define depth of top layer (for N movement).
        - define N enrichment ratio.
        - define Alpha coefficient (dissolved N calibration factor).
        - define Beta coefficient (particulate N calibration factor).
        - select source data-file (can be attached to project or loaded via the inputs):
            - select which time-series in the data-file represents "Inorganic Nitrate-N (top layer) (kg/ha)";
            - select which time-series in the data-file represents "Inorganic ammonium N (top layer) (kg/ha)"; and
            - select which time-series in the data-file represents "Organic N (top layer) (kg/ha)".
        - define a scaling (calibration) factor for scaling organic N store.
    - user defined profile:
        - uses the same parameters defined in "Imported time-series", except that the time-series are not read in from a datafile, but from a single annual profile of soil nitrate loads (kg/ha) and dates (Julian day).

Note that both the Rattray and Fraser methods of estimating dissolved N in runoff DO NOT use an estimate of Nitrate-N stored in top layer (kg/ha) in their calculations. However, due to a bug in the controller, they DO NEED to have a time-series of these values set up in order to run. Unfortunately, there is no option visible in the user-interface to do this when one of these methods are selected. Nevertheless, the software can be tricked into seeing an input time-series by first by selecting "Imported time-series" and connecting the time-series, and then switching over to the method of Rattray or Fraser. This bug will be rectified in the web-version of HowLeaky.

10.1 Calculate dissolved Nitrate-N in runoff

There are three different methodologies for calculating dissolved Nitrate-N in runoff:

- Option 1 - Victorian Department of Primary Industries (DPI) methodology (“imported time-series” or “user-defined profile);
- Option 2 - methodology of Rattray (“Rattray empirical model”); and
- Option 3 - methodology of Fraser (“Fraser empirical model”).

10.1.1 Option 1- Victorian DPI methodology

This option was developed by ideas suggested by David Freebairn and Brett Robinson. It is based on the concept that soil and runoff water mixing increase up to a maximum of a constant value k (parameter that regulates mixing of soil and runoff water with a suggested value is 0.5):

$$N\_conc_{runoff} = N\_conc_{soil} \times k \times \left(1 - e^{-cv \times runoff}\right) \tag{10-1}$$

where:

- N_conc_{runoff} is the nitrate concentration in the runoff (mg/L);
- cv is a parameter that describes the curvature of change in soil and water runoff at increasing runoff values (initial guess is 0.2); and,
- $Runoff$ is daily runoff in mm.

The soil nitrate concentration in the surface layer (0-2 cm) N_conc_{soil} (mg N/kg) is derived from the nitrate load (N_load_{soil}in kg/ha) in the surface layer exported from ***DairyMod*** (or a user-defined profile):

$$N\_conc_{soil} = \frac{\alpha \times 100 \times N\_load_{soil}}{d \times \rho} \tag{10-2}$$

where:

- ρ is the soil density (tm^{-3});
- d is depth of surface soil layer (in mm; that is, 20 mm); and,
- α is a conversion factor that can be used also for calibration.

The dissolved N load (N_load_{runoff}, kg/ha) in runoff is:

$$N\_load_{runoff} = \frac{N\_conc_{runoff} \times runoff}{100} \tag{10-3}$$

10.1.2 Option 2 - Method of Rattray

Rattray’s methodology calculates dissolved inorganic nitrogen (DIN which includes N03 N plus NH4 N) in runoff (N_conc_{runoff}) in response to a fertiliser application. It does not calculate the runoff loading in either the soil or runoff water as did the previous (Victorian DPI) methodology.

The method inputs a sequence of fertiliser application rates and dates. On each day of the simulation, it monitors effective-rainfall (rainfall + non-infiltrated irrigation water) and keeps track of the accumulation of this amount ($cumrain$) each time nitrate is applied. Once an effective rainfall amount that causes runoff is obtained, the DIN concentration in the runoff can be calculated:

$$N\_conc_{runoff} = \frac{lastnappliedrate}{a} \times cumrain^{-b} \qquad (10\text{-}4)$$

where:

- lastnappliedrate is the most recent application rate from the input time-series; and
- a and b are the “Power Fit Alpha and Beta values” from the input parameters.

If runoff does not occur during the rainfall event, then:

$$N\_conc_{runoff} = 0 \qquad (10\text{-}5)$$

If neither rainfall nor runoff occurs, then define the concentration as “Not-defined”, to produce a discontinuous time-series of concentration outputs:

$$N\_conc_{runoff} = \mathrm{NotDefined} \qquad (10\text{-}6)$$

Finally, to ensure that this estimate is confined to the maximum and minimum concentrations (maxconc and minconc) defined in the input parameters:

$$N\_conc_{runoff} = Min(maxconc, Max(minconc, N\_conc_{runoff})) \qquad (10\text{-}7)$$

10.1.3 Option 3 - Methodology of Fraser

Fraser’s methodology is very similar to that of Rattray, in that it calculates dissolved inorganic nitrogen (DIN which includes N03 N plus NH4 N) in runoff in response to an applied fertiliser rate (input as a sequence of rates and dates) and does not calculate loadings. It also monitors effective rainfall (effectiverain) but does not test whether this is a positive real number or if runoff is occurring. Therefore, regardless of whether rainfall or runoff are occurring:

$$\begin{aligned} N\_conc_{runoff} = {} & \frac{1}{k} lastnappliedrate \\ & + Max\left(lowlimit, \left(N\_conc^{*}_{runoff}\right.\right. \\ & \left.\left. - Max\left(N_{conc}{}^{*}_{runoff} \times DL, effectiverain \times RL\right)\right)\right) \end{aligned} \qquad (10\text{-}8)$$

Where:

- k is the soil water/runoff mixing factor (input parameter);
- lastnappliedrate is the last recorded fertiliser application rate (input parameter);
- lowlimit is the lower limit DIN concentration (approach rainfall) (input parameter);
- $N\_conc^{*}_{runoff}$ is yesterday’s N runoff concentration;
- DL is the daily loss proportion (input parameter); and,
- RL is the rainfall loss-DIN per mm of effective rainfall.

10.2 Calculate dissolved Nitrate-N in leaching

Calculation of dissolved N in the leaching water requires a predefined knowledge of the Nitrate-N stored in the bottom layer of the soil through time, which we derive from our imported time-series or profile data. We start our calculations estimating the nitrate concentration in soil water contributing to leaching (mg/l). Therefore, in the bottom layer of our soil profile:

$$N\_conc_{leaching} = \frac{N\_conc_{soil\_bot}}{PAWC_{bot}} \tag{10-9}$$

where:

- $N\_conc_{soil\_bot}$ is the nitrate concentration in the deepest soil layer (kg/ha) extracted from the input time-series or profile; and,
- $PAWC_{bot}$ is the soil water between air-dry water content and saturated water content (mm) of the deepest soil layer.

Nitrate-N leaching load (kg /ha) is then calculated:

$$N\_load_{\ leaching} = \frac{N\_conc_{leaching}}{1000000} \times drainage \times 10000 \times LE \tag{10-10}$$

where:

- LE is the leaching efficiency parameter (input parameter) portioning soil water nitrate concentration into various pathways (often taken as 0.5); and,
- $drainage$ is the daily drainage (mm).

10.3 Calculate particulate Nitrate-N in runoff

Particulate Nitrate-N Losses in runoff (kg/ha) are modelled in a similar way to particulate P. The N concentration in the soil (mg/kg) is calculated as:

$$N\_conc_{soil} = \frac{alpha \times 100 \times N\_load_{soil}}{depth \times BulkDensity} \tag{10-11}$$

where:

- $alpha$ is a conversion factor to adjust units (input parameter);
- N_load_{soil} is the total N load of the soil (kg/ha) and is the sum of the organic and inorganic N loads at 0-2 cm from ***DairyMod***. (As N_load_{soil} will be derived from ***DairyMod*** in kg/ha, it needs to be converted to mg/kg).

Then, the particulate N loading is:

$$N\_load_{\ particulate} = \frac{beta \times erosion \times SedDelRatio \times N\_conc_{soil} \times NER}{10000000} \tag{10-12}$$

where:

- $N\_load_{\ particulate}$ is the particulate N load (kg/ha);
- $beta$ is a conversion factor to adjust units and can be used as a calibration factor (input parameter);
- $erosion$ is the gross erosion (kg/ha);
- $SedDelRatio$ is the sediment delivery ratio (INPUT from soil parameters); and,

- NER is the Nitrogen enrichment ratio (input parameter), which is unitless and defined similarly to PER (p_enrich for P).

An addition output $PNHLC$ is also calculated as was requested by Victorian DPI for compatibility with the ***CatchMODS*** model:

$$PNHLC = \frac{N\_load_{\ particulate}}{SedDelivRatio \times usle\_ls\_factor} \qquad 10\text{-}13$$

11 Solutes submodel

The solute submodel in ***HowLeaky*** is an experimental model to estimate solute leaching which, to the best of this author's knowledge, has not been used in any referenced studies. It has undergone little validation and is loosely based on an older algorithm from the ***PERFECT*** model which is not documented in the ***PERFECT*** manual. Therefore, there appears to be no recorded references for the origins of these equations.

The model works by providing an initial solute concentration across the soil layers (defined using a range of options) as well as rainfall and irrigation water solute concentrations. A mixing coefficient is also provided to then route the solute through the soil profile when rainfall or irrigation is sufficient to cause drainage.

Outputs include:

- total soil solute load in kg/ha;
- total soil solute concentration in mg/kg of soil;
- total soil water solute concentration in mg/L of soil water;
- leachate solute concentration in mg/L of soil water;
- leachate solute load in kg/ha;
- rainfall solute concentrate in mg/kg of soil;
- rainfall solute load in kg/ha;
- irrigation solute concentration in in mg/kg of soil; and
- irrigation solute load in kg/ha.

Initial solute concentrations must be defined through the input parameters. A range of 11 options can be selected by the user which allows a single concentration across all soil layers ("Constant") or different concentration in up to 10 soil layers as follows:

- constant;
- define layer 1;
- define layers 1 to 2;
- define layers 1 to 3; and
- Define layers 1 to 10.

Depending on which one of these options is selected, the user is required to provide an initial solute concentration (mg/kg) for the specified layer, and a default initial solute concentration for other layers (mg/kg). The user must also specify input solute concentrations in rainfall and irrigation water (mg/L), along with a mixing coefficient to calculate loadings.

Note that the methodology for calculating a solute mass balance in the soil can be quite complex due to converting between water and soil solute concentrations and dealing with different bulk densities of the soil layers. To express the equations as simply as possible, a longer notation is used below (which is compatible with the computer code notation) with units expressed in many of the variable names.

11.1 Calculating solute loads from rainfall

On any day, calculations proceed by calculating the solute concentration added to the soil (mg/kg soil) from any rainfall or irrigation water which may occur. To undertake the conversion between mg/L water to mg/kg soil, the amount of soil in the first soil layer must be determined:

$$kgs\_soil\_in\_layer\_1 = BulkDensity_0 \times 1000.0 \times depth_1 \times \frac{10000}{1000} \qquad 11\text{-}1$$

Then to work out the rainfall contribution, when rain is greater than 0:

$$solute\_conc\_rainfall\_mg\_per\_kg = SoluteRainfallConcentration\_mg\_per\_L \times (rain - runoff) \times 10000 \tag{11-2}$$

Then update the solute concentration in the top soil layer (mg/kg) by adding the concentration from the rainfall with the existing amount in that layer (from the previous day):

$$solute\_conc\_layer\_mg\_per\_kg_0 = solute\_conc\_layer\_mg\_per\_kg_0 + solute\_conc\_rainfall\_mg\_per\_kg \tag{11-3}$$

where:

- the subscript “0” denotes layer 1.

Finally, work out the total rainfall contribution to solute loading in kg/ha by accounting for the amount of soil in layer one:

$$solute\_conc\_rainfall\_kg\_per\_ha = solute\_conc\_rainfall\_mg\_per\_kg \times \frac{kgs\_soil\_in\_layer\_1}{1000000} \tag{11-4}$$

11.2 Calculating solute loads from irrigation

To work out the irrigation contribution, if $irrigation\_amount$ is greater than 0:

$$solute\_conc\_irrig\_mg\_per\_kg = SoluteIrrigationConcentration\_mg\_per\_L \times irrigation\_amount \times 10000 \tag{11-5}$$

Then update the solute concentration in the top soil layer (mg/kg) by adding the concentration from the irrigation water with the current amount in that layer:

$$solute\_conc\_layer\_mg\_per\_kg_0 = solute\_conc\_layer\_mg\_per\_kg_0 + solute\_conc\_irrig\_mg\_per\_kg \tag{11-6}$$

Finally, work out the total irrigation contribution to the solutes in kg/ha by accounting for the amount of soil in layer one:

$$solute\_conc\_irrig\_kg\_per\_ha = solute\_conc\_irrig\_mg\_per\_kg \times \frac{kgs\_soil\_in\_layer\_1}{1000000} \tag{11-7}$$

11.3 Calculating the solute mass balance

To get a mass balance, the variable that will be accumulated must first be initialised. Firstly, total soil mass in kg is set to 0:

$$total\_soil\_mass\_kg = 0 \tag{11-8}$$

Then the soil water amount relative to "oven-dry" limit is set to 0. Note that in the computer code, the notation "$\_\mathrm{OD}$ " has been used to refer to "oven-dry":

$$total\_SW\_rel\_OD = 0 \tag{11-9}$$

Finally, the total soil solute amount (kg/ha) is set to 0:

$$total\_soil\_solute\_kg\_per\_ha = 0 \tag{11-10}$$

Then route solutes down through the layer. Therefore, for each soil layer i, starting from top to bottom:

$$SW\_rel\_OD_i \ = \ SoilWater\_rel\_wp_i + Wilting\_Point\_RelOD\_mm_i \tag{11-11}$$

$$total\_SW\_rel\_OD = \ total\_SW\_rel\_OD + SW\_rel\_OD_i \tag{11-12}$$

$$StartOfDay\_SW\_rel\_OD_i = SW\_rel\_OD_i + Seepage_i \tag{11-13}$$

If $\mathrm{StartOfDay\_SW\_rel\_OD_i}$ and $\mathrm{SW\_rel\_OD_i}$ are both greater than zero, then estimate the amount of solute in the soil (kg):

$$kgs\_soil\_in\_layer_i \ = \ BulkDensity_i \times 1000 \times (depth_{i+1} - depth_i) \times \frac{10000}{1000} \tag{11-14}$$

To accumulate the total soil mass:

$$total\_soil\_mass\_kg = total\_soil\_mass\_kg + kgs\_soil\_in\_layer_i; \tag{11-15}$$

To initialise the potential drained solute in mg to zero:

$$potential\_drained\_solute\_mg = 0; \tag{11-16}$$

Then to calculate the potential drained solute in mg:

$$potential\_drained\_solute\_mg = \left(\frac{solute\_conc\_layer\_mg\_per\_kg_i \times kgs\_soil\_in\_layer}{StartOfDay\_SW\_rel\_OD}\right) \times Seepage_{\ i+1} \quad (11\text{-}17)$$

Then calculate the actual drained loadings in the layer:

$$actual\_drained\_solute\_mg = SoluteMixingCoefficient \times potential\_drained\_solute\_mg \quad (11\text{-}18)$$

where:

- SoluteMixingCoefficient is an input parameter ranging from 0-1 (unitless).

Then take the drained solute load away from the balance in the layer:

$$solute\_conc\_layer\_mg\_per\_kg_i = solute\_conc\_layer\_mg\_per\_kg_i - \frac{actual\_drained\_solute\_mg}{kgs\_soil\_in\_layer} \quad (11\text{-}19)$$

Calculate the solute load in the layer:

$$solute\_load\_layer\_kg\_per\_ha_{\ i} = \frac{solute\_conc\_layer\_mg\_per\_kg_i \times kgs\_soil\_in\_layer}{1000000} \quad (11\text{-}20)$$

Keep track of total load:

$$total\_soil\_solute\_kg\_per\_ha = total\_soil\_solute\_kg\_per\_ha + solute\_load\_layer\_kg\_per\_ha_i \quad (11\text{-}21)$$

Calculate solute concentration in layer:

$$solute\_conc\_layer\_mg\_per\_L_i = \frac{solute\_load\_layer\_kg\_per\_ha_i}{SW\_rel\_OD \times 10.0} \times 1000 \quad (11\text{-}22)$$

Push solute into next layer OR calculate leaching (deep drainage) loadings. If bottom layer:

$$kgs\_soil\_in\_next\_layer = BulkDensity_{i+1} \times 1000 \times (depth_{i+2} - depth_{i+1}) \times \frac{10000}{1000} \quad (11\text{-}23)$$

Then the solute concentrate in the layer is:

$$\begin{aligned} solute\_conc\_layer\_mg\_per\_kg_{i+1} \\ = solute\_conc\_layer\_mg\_per\_kg_{i+1} + \frac{actual\_drained\_solute\_mg}{kgs\_soil\_in\_next\_layer} \end{aligned} \quad (11\text{-}24)$$

Otherwise, if upper layer:

$$solute\_leaching\_load\_kg\_per\_ha = \frac{actual\_drained\_solute\_mg}{1000000} \quad (11\text{-}25)$$

Then the solute leaching concentrate is:

$$solute\_leaching\_conc\_mg\_per\_L = solute\_conc\_layer\_mg\_per\_L_i \quad (11\text{-}26)$$

Finally, after routing has been completed:

$$total\_soil\_solute\_mg\_per\_kg = \frac{total\_soil\_solute\_kg\_per\_ha}{total\_soil\_mass\_kg} \times 1000000 \quad (11\text{-}27)$$

And:

$$total\_soil\_solute\_mg\_per\_L = \frac{total\_soil\_solute\_kg\_per\_ha}{total\_SW\_rel\_OD \times 10} \times 1000 \quad (11\text{-}28)$$

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Appendix 1 - Soil input parameters

A1.1 Parameter descriptions

Input parameter	Description
Number of Horizons **Name in file:** `HorizonCount` **Name in code:** `LayerCount`	Number of soil layers/horizons **Range:** 2 to 10
Layer Depth (Cumulative) (mm) **Name in file:** `LayerDepth` **Name in code:** `Depths`	Depth to the bottom of each soil layer defined by "Number of Horizons". **Range:** 100 to 20,000 **Suggested Values:** Keep the surface layer thickness as 100 mm. The deepest layer should be deeper than the maximum root depth of the deepest rooting vegetation you will be modelling.
Air dry moisture (%Vol) **Name in file:** `InSituAirDryMoist` **Name in code:** `soil_air_dry_limit_percent`	This is the moisture content when the soil is air-dry (40o C). It is usually much less than the lower limit of plant-available moisture. A value is needed for each soil layer defined by "Number of Horizons" and "Layer Depth (Cumulative)". However, values in deeper soil layers have no effect because evaporation only occurs in the top two soil layers. **Range:** 0 to 100% (<Wilting point) **Suggested Values:** Depends on soil type/properties and is largely independent of type of vegetation. If no other data, use one third of wilting point soil moisture content (personal communication, D. Silburn, 2009) ADMC% = -0.076 +0.117 Clay% R^2 = 0.648). AMDC% = -1.37 + 0.42*15barMC% (R^2 = 0.849). AMDC% = 1.34 + 0.15 CEC (R^2 = 0.881). (Shaw 1994; Figure 2 & Table 6).
Wilting point (%Vol) **Name in file:** `WiltingPoint` **Name in code:** `soil_lower_limit_percent`	Wilting point is the lower limit of soil moisture content for plant water use (the moisture content at which plants permanently wilted). A value is needed for each soil layer defined by "Number of Horizons" and "Layer Depth (Cumulative)". **Range:** 0 to 100% (< Field Capacity) **Suggested Values:** Depends on soil type/properties and the type of vegetation. Wilting point has been measured or estimated for a reasonably large number of soils under cropping in Australia and a more limited number of soils under other vegetation types (e.g. pastures, woodlands and forests). Values have been collated for **HowLeaky** for various regions in Australia. Wilting point can also be estimated (with variable accuracy) from other soil properties using various equations (pedotransfer functions such as PAWCER; Littleboy, 2002).

Field capacity (%Vol) **Name in file:** `FieldCapacity` **Name in code:** `soil_upper_limit_percent`	Field capacity (or drained upper limit) is the water content in the soil after free water drains. A value is needed for each soil layer defined by "Number of Horizons" and "Layer Depth (Cumulative)". **Range:** 0 to 100% (< Saturation limit) **Suggested Values:** Depends on soil type/properties and is largely independent of type of vegetation. Field capacity can also be estimated (with variable accuracy) from other soil properties using various equations (pedotransfer functions such as PAWCER; Littleboy, 2002).
Sat. water content (%Vol) **Name in file:** `SatWaterCont` **Name in code:** `soil_saturation_limit_percent`	Saturated water content (SAT) is the soil moisture content of the soil layer when saturated. It is equal to total porosity (which can be calculated from bulk density) except where a small amount of air is entrapped in the soil. A value is needed for each soil layer defined by “Number of Horizons” and “Layer Depth (Cumulative)”. **Range:** 0 to 100% **Suggested Values:** Depends on soil type/properties and is largely independent of type of vegetation. Saturated water content can also be estimated (with variable accuracy) from other soil properties using various equations (pedotransfer functions such as PAWCER; Littleboy, 2002).

Maximum drainage from layer (mm/day)
Name in file:
`MaxDailyDrainRate`
Name in code:
`max_layer_drainage_mm_per_day`
	Controls the maximum rate of drainage downwards from each soil layer ("Layer Depth (Cumulative)") when it is saturated and the deep drainage below the deepest soil layer. Drainage is also influenced by drainable porosity ("Saturated water content" minus "Field capacity").
	Range: 0 to 1000 mm/day
	Suggested Values: large values (e.g. 100 mm/day) should be used in upper soil layers on all soils to prevent excessive “overflow”. Maximum drainage rate can also be estimated (with variable accuracy) from other soil properties using various equations (pedotransfer functions such as Shaw (1995); FIR (mm/day) = 30.69 *10^ (-0.241* ESP^0.5) where FIR is final infiltration rate measured in large ponds and ESP is exchangeable sodium percentage at 0.9m soil depth.

Bulk density (g/cm^3) **Name in file:** `BulkDensity` **Name in code:** `BulkDensity`	Bulk density of the soil. Used in Pesticide, Nitrate and Solute calculations. This must be specified for each layer of the soil. **Range:** 0.5 to 5 **Suggested Values:** Typically, 1.0 to 1.5 g/cm^3 Bulk density can also be estimated (with variable accuracy) from other soil properties using various equations (pedotransfer functions such as PAWCER; Littleboy, 2002). For Vertosols, bulk density should be the bulk density of soil at drained upper limit.

<table>
<tr>
<td>Stage 2 evap., Cona (mm/day^0.5)

Name in file:
<code>Stage2SoilEvap_Cona</code>
Name in code:
<code>Cona</code></td>
<td>Cona represents the slope of the Stage II drying curve when cumulative soil evaporation is plotted against the square root of time.
Range: 0 to 10 mm/day^0.5
Suggested Values: e.g. 4 mm/day^0.5. Cona can be estimated from clay content using a modified form of the procedure described by Ritchie and Crum (1989). Recommended values for Cona are presented in the table below. Alternatively, Cona can be calculated directly from lysimeter data if available (cf Ritchie 1972).

<table>
<tr><th>Clay (%)</th><th><i>Cona</i> (mm/day^0.5)</th></tr>
<tr><td>10</td><td>3.5</td></tr>
<tr><td>20</td><td>3.75</td></tr>
<tr><td>30</td><td>4.0</td></tr>
<tr><td>40</td><td>4.0</td></tr>
<tr><td>50</td><td>4.0</td></tr>
<tr><td>60</td><td>3.75</td></tr>
<tr><td>70</td><td>3.5</td></tr>
<tr><td>80</td><td>3.5</td></tr>
</table>
</td>
</tr>
<tr>
<td>Stage 1 evap. limit, U (mm)

Name in file:
<code>Stage1SoilEvap_U</code>
Name in code:
<code>Stage1SoilEvapLimit</code></td>
<td>Stage 1 evaporation limit U is the maximum amount of drying that can occur during Stage 1 evaporation. That is, Stage 1 soil evaporation will equal the potential soil evaporation rate until the cumulative Stage 1 drying exceeds the value of the parameter U (the upper limit of Stage 1 drying).
Range: 0 to 20 mm
Suggested Values: U can be estimated from clay content using a modified form of the procedure described by Ritchie and Crum (1989). Recommended values for U are presented in the table below. Alternatively, U can be calculated directly from lysimeter data if available (cf Ritchie, 1972).

<table>
<tr><th>Clay (%)</th><th>U (mm)</th></tr>
<tr><td>10</td><td>6.75</td></tr>
<tr><td>20</td><td>8.5</td></tr>
<tr><td>30</td><td>9.0</td></tr>
<tr><td>40</td><td>9.5</td></tr>
<tr><td>50</td><td>9.0</td></tr>
<tr><td>60</td><td>8.25</td></tr>
<tr><td>70</td><td>7.5</td></tr>
<tr><td>80</td><td>7.0</td></tr>
</table>
</td>
</tr>
<tr>
<td>Runoff curve no. (bare soil)

Name in file:
<code>RunoffCurveNumber</code>
Name in code:
<code>RunoffCurveNumber</code></td>
<td>The curve number for soil with no cover. The runoff Curve Number (CN) partitions rainfall into runoff and infiltration, using a modification of the USDA method that relates CN to soil moisture content each day (Williams & La Seur 1976, Williams et al., 1985), rather than to antecedent rainfall. In PERFECT and HowLeaky, this is modified further to adjust CN for cover and for soil surface roughness caused by tillage (optional). The input parameter is the CN for bare soil at average antecedent moisture content (CN2bare).
Range: 0 to 100</td>
</tr>
</table>

	Suggested Values: Usually between 50 and 100 for agricultural soils. For example (values extracted from sample soil files): Euchrozem - Kandosol or Ferrosol: 88; Ferrosol: 74 ; Grey and Black Vertosols: 73; Kandosol: 85 ; Rudosol: 94; Tenosol: 84

CN Reduction 100% cover
Name in file:
`RedInCNAtFullCover`
Name in code:
`CurveNumberReduction`
	Maximum reduction in curve number at 100% cover. That is, the reduction in runoff Curve Number (CN2) below CN2bare (Runoff curve number (bare soil)) at 100% cover. Used to calculate the effect of cover on runoff.
	Range: 0 to 30
	Suggested Values: 20 for well-structured Black and Grey Vertosols (Silburn & Freebairn 1992; Littleboy et al., 1992), - 40 for soils with a hard-setting surface (Owens et al., 2003). Higher for permanent/living cover (eg pasture) than for temporary cover (eg crop residues). – Generally higher for soil with higher CN2bare.

CN Reduction – Tillage **Name in file:** `MaxRedInCNDueToTill` **Name in code:** `MaxRedInCNDueToTill`	Reduction in runoff Curve Number (CN2bare) when a tillage operation occurs (optional). Used to model effects of soil surface roughness, cause by tillage, on runoff (if selected) in conjunction with “Rainfall to 0 roughness”, based on Littleboy et al. (1996a). **Range:** 0 to 30 **Suggested Values:** Rainfall to 0 roughness = 0 and CN reduction tillage = 0 are the preferred default option, unless modelling of tillage/roughness effects on runoff is an objective of the study, or there is evidence of a large effect of tillage/roughness on runoff. Tillage/roughness effects on runoff are more pronounced on low slopes. Littleboy et al. (1996a) found Cnred = 5 and rain to 0 roughness = 200 mm for tillage to 10 cm, Cnred = 10 and for rain to 0 roughness = 400 mm for tillage to 20 cm on a hard setting Alfisol in India.

Rainfall to 0 roughness (mm)
Name in file:
`RainToRemoveRough`
Name in code:
`RainToRemoveRoughness`
	Cumulative rainfall required to remove surface roughness.
	Range: 0 to 100
	Suggested Values: Typically, from 0 and 400mm for agricultural soils. For example (values extracted from sample soil files): Euchrozem – Kandosol or Ferrosol: 100mm; Ferrosol: 400mm; Grey Vertosol: 400mm; Kandosol: 50mm ; Rudosol: 400mm; Tenosol: 0mm

USLE K factor (metric)
Name in file:
`USLE_K`
Name in code:
`USLE_k_Factor`
	USLE K factor is the soil erodibility factor (K) of the Universal Soil Loss Equation (USLE, Renard et al., 1993). It defines the inherent susceptibility of a soil to erosion per unit of rainfall erosivity and is defined for set cover and crop condition (bare soil, permanent fallow, C = 1), slope and length of slope (LS factor = 1) and practice factor (P=1).
	Range: 0 to 5
	Suggested Values: depends on soil type/properties. For Australian soils, (see Loch & Rosewell, 1992;

	Loch et al., 1999; Rosewell & Edwards, 1988; Rosewell & Loch, 1995). Note these references give values in SI units. Loch, R.J. and Rosewell, C.J. (1992). Laboratory methods for measurement of soil erodibilities (K factors) for the universal soil loss equation. Australian Journal of Soil Research, 30,233 248. Loch, R.J., Slater, B.K. and Devoil, C. (1999). Soil erodibility (Km) for some Australian soils. Australian Journal of Soil Research, 36. Rosewell, C.J. and Edwards, K. (1988). SOILOSS – a program to assist in the selection of management practices to reduce erosion. Soil Conservation Service of New South Wales, Technical Handbook Number 11. Rosewell, C.J. and Loch, R.J. (1995). Soil Erodibility – Water. In, Soil Physical Measurement and Interpretation for Land Evaluation. Australian Soil and Land Survey Handbook Series Volume 5. Australian Collaborative Land Evaluation Program, CSIRO, Canberra. Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder, D.C. (1993). Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook 703, United States Department of Agriculture.

USLE P factor
 	
Name in file:
`USLE_P`
Name in code:
`USLE_p_Factor`
	USLE P factor is the practice factor (P) of the Universal Soil Loss Equation (USLE; Renard et al., 1993). It defines effects of conservation practices other than those related to cover and cropping/soil water use practices. A value of 1.0 indicates no such practices and is considered the norm.
	Range: 0 to 5
	Suggested Values: 1.0 is the preferred default option, unless a conservation practice (other than cover and cropping/soil water use practices) which causes a known reduction in soil loss (see Renard et al., 1993). The P factor can be used to represent the effect of rock cover in reducing soil loss, if a suitable value is known.

Field slope (%) **Name in file:** `FieldSlope` **Name in code:** `FieldSlope`	Slope of the paddock (%). **Range:** 0 to 100% **Suggested Values:** depends on land conditions.
Slope length (m) **Name in file:** `SlopeLength` **Name in code:** `SlopeLength`	Slope length is the distance down the slope (or contour bank spacing), used to calculate the USLE slope-length factor (LS) using the algorithm from the Revised USLE (Renard et al., 1993). It has no effect on other processes. **Range:** 0 to 1000m **Suggested Values:** depends on land conditions

Rill/interrill ratio (0-1)
Name in file:
`RillRatio`
Name in code:
`XXXX`
	Rill/interrill ratio
	Range: 0 to 1
	Suggested Values: depends on field conditions.

Soil cracking
Name in file:
`SoilCrack`
Name in code:
`SimulateSoilCracking`
	A value of YES turns on the option for some rainfall (defined by "Max crack infilt.") to infiltrate below soil layer 2 directly via cracks. Infiltration via crack will only occur when daily rainfall is greater than 10 mm and soil moisture content in the upper two soil layers is less than 30% of field capacity. Cracks extend down through all layers where soil moisture is less than 30% of field capacity. Infiltration occurs into the lowest “cracked” layer first and any layer can only fill to 50% of field capacity. This option is affected by the number and thickness of layers used.
	Range: YES or NO
	Suggested Values: NO – this is not commonly used.

Max crack infilt. (mm) Visible when using “Soil Cracking” option is set to “YES”. **Name in file:** `MaxInfiltIntoCracks` **Name in code:** `MaxInfiltIntoCracks`	Maximum infiltration into soil cracks. **Range:** 0 to 100mm **Suggested Values:** Depends on field conditions
Sediment Delivery Ratio **Name in file:** `SedDelivRatio` **Name in code:** `SedDelivRatio`	Sediment delivery ratio is used in the erosion and nitrate calculations. It’s used to calculate the sediment concentration in runoff water from total eroded amount (t/ha). **Range:** 0.0001 to 1 **Suggested Values:** Typical value is 0.1

A1.2 Sample soil parameter values

A1.2.1 Average clay loam (PAWC 170 mm)

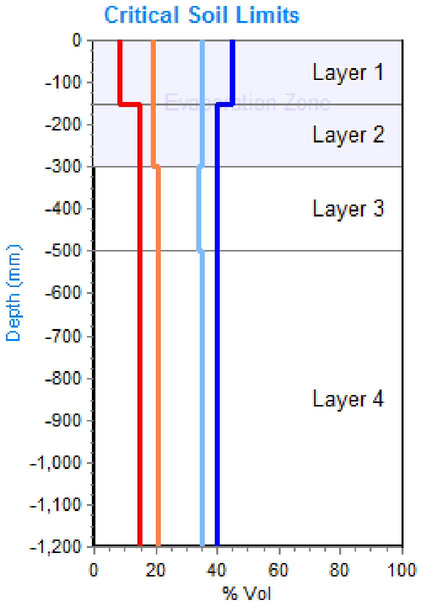
Based on Clay loam over medium clay (PAWC 170mm)

Source: APSOIL Database (CSIRO)

LB code:QRN; David Maschmedt Description: 0-6cm Clay Loam 2.5YR 3/4; 6-45cm Medium-heavy Clay 2.5YR 3/3; 45-85cm Medium Clay 2.5YR 4/6; 85-135cm Medium Clay 2.5YR 4/8 Roots: Wheat 130cm. Moderate-high clay strongly duplex soil with moderate bulk den

Number of Horizons	4	
Layer Depths	150, 300, 500, 1200	mm
Air Dry Limit	8, 15, 15, 15	%Vol
Wilting Point	19, 19, 21, 21	%Vol
Field Capacity	35, 35, 34, 35	%Vol
Saturation Limit	45, 40, 40, 40	%Vol
PAWC	24, 24, 26, 98 (Total = 172mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 25	mm/day
Max Daily Drainage Volume	15, 7.5, 12, 35	mm
Bulk Density	1.2, 1.3, 1.3, 1.4	g/cm^3
Stage 2 Soil Evaporation, Cona	4	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	85	
Reducation in CN At Full Cover	20	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	1	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.14	(0-1)

Clay loam over medium clay (Quorn No605) has been extracted from the ASOIL Database file Soil Type: Clay loam over medium clay Data source: Characterisation 2008 by University of Adelaide CSIRO Sustainable Ecosystems and Rural Solutions Jamestown Comments: LB code:QRN; David Maschmedt Description: 0-6cm Clay Loam 2.5YR 3/4; 6-45cm Medium-heavy Clay 2.5YR 3/3; 45-85cm Medium Clay 2.5YR 4/6; 85-135cm Medium Clay 2.5YR 4/8 Roots: Wheat 130cm. Moderate-high clay strongly duplex soil with moderate bulk density.



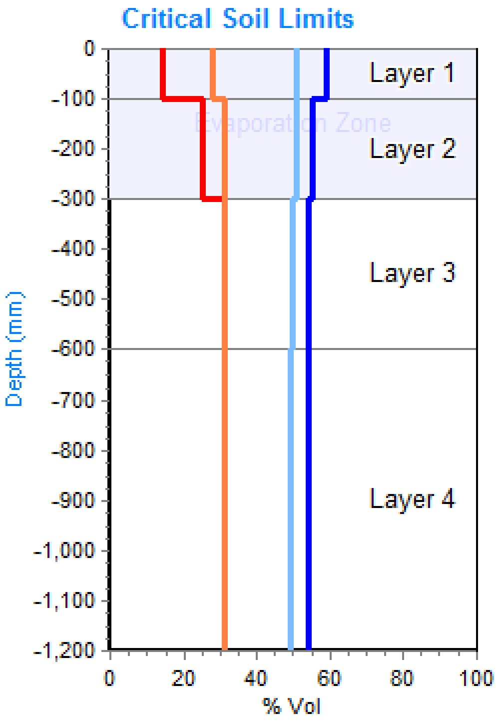
A1.2.2 Average heavy clay (PAWC 230mm)

Based on Black Vertosol-Irving (Greenmount No067) (PAWC 230mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	100, 300, 600, 1200	mm
Air Dry Limit	14, 25, 31, 31	%Vol
Wilting Point	28, 31, 31, 31	%Vol
Field Capacity	51, 51, 50, 49	%Vol
Saturation Limit	59, 55, 54, 54	%Vol
PAWC	23, 40, 57, 108 (Total = 228mm)	mm
Max Daily Drainage Rate (mm/day)	100, 100, 5, 2	mm/day
Max Daily Drainage Volume	8, 8, 12, 30	mm
Bulk Density	1, 1.1, 1.2, 1.3	g/cm^3
Stage 2 Soil Evaporation, Cona	3	mm/day^0.5
Stage1 Soil Evaporation, U	5	mm
Runoff Curve Number	73	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	1	
Rainfall To Remove Roughness	1	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks		mm
Sediment Delivery Ratio	0.14	(0-1)

Black Vertosol-Irving (Greenmount No067) from ApSoil Not used in this analysis as used revised soil water from reworked LL and PWC values. Not likely to impact to any degree DMF 111021



A1.2.3 Average light clay (PAWC 125mm)

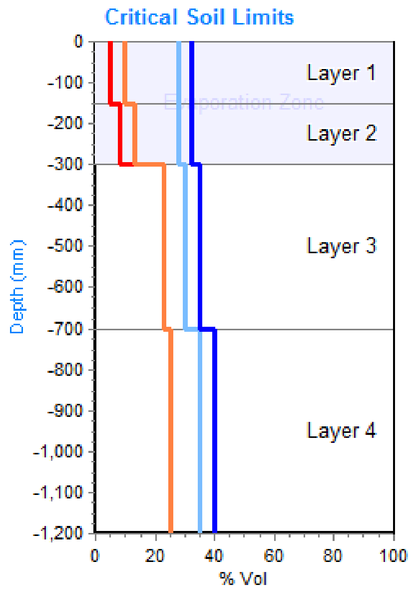
Based on Heavy Red Kandosol (Greenethorpe No619-YP) (PAWC 125)

Source: APSOIL Database (CSIRO)

Original data source: YP. Made by James Hunt, BCG modified version of SW Slopes-Greenthorpe from M. Robertson & J. Kirkegaard (CSIRO PI), requested by Farmlink. CLL/AirDry data taken from SW measurements made by Tony Swan of CSIRO PI in R. Taylors Finns paddock at Greenthorpe 19 April 2007. DUL is estimated based on CLL and original soil. OC in top 1 m measured.

Number of Horizons	4	
Layer Depths	150, 300, 700, 1200	mm
Air Dry Limit	5, 8, 23, 25	%Vol
Wilting Point	10, 13, 23, 25	%Vol
Field Capacity	28, 28, 30, 35	%Vol
Saturation Limit	32, 32, 35, 40	%Vol
PAWC	27, 22.5, 28, 50 (Total = 128mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 10	mm/day
Max Daily Drainage Volume	6, 6, 20, 25	mm
Bulk Density	1.3, 1.3, 1.3, 1.5	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	75	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on Heavy Red Kandosol (Greenethorpe No619-YP) has been extracted from the ASOIL Data source: YP. Made by James Hunt, BCG modified version of SW Slopes-Greenthorpe from M. Robertson & J. Kirkegaard (CSIRO PI), requested by Farmlink. CLL/AirDry data taken from SW measurements made by Tony Swan of CSIRO PI in R. Taylors Finns paddock at Greenthorpe 19 April 2007. DUL is estimated based on CLL and original soil. OC in top 1 m measured. Comments: All CLL estimated.



A1.2.4 Average sand loam (PAWC 80mm)

Based on but modified from Yellow Deep Sand (Buntine)

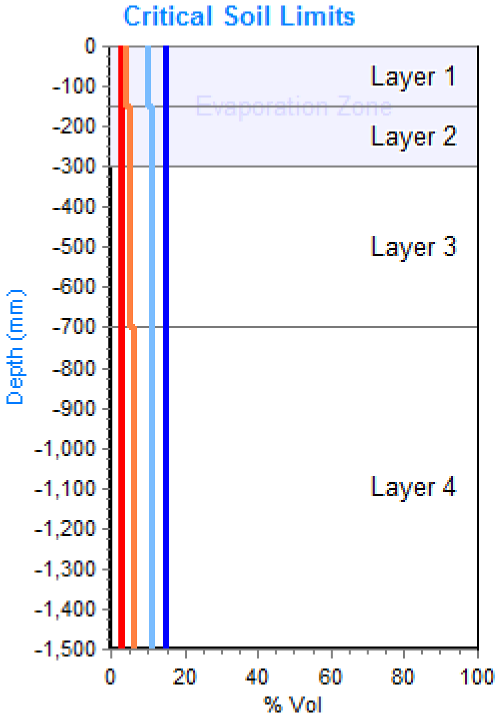
Source: APSOIL Database (CSIRO)

Original Source: YP. Collected by CSIRO as part of the GRDC SIP09 Precision Agriculture Project.

Birch12

Number of Horizons	4	
Layer Depths	150, 300, 700, 1500	mm
Air Dry Limit	3, 3, 3, 3	%Vol
Wilting Point	4, 5, 5, 6	%Vol
Field Capacity	10, 11, 11, 11	%Vol
Saturation Limit	15, 15, 15, 15	%Vol
PAWC	9, 9, 24, 40 (Total = 82mm)	mm
Max Daily Drainage Rate (mm/day)	50, 50, 50, 50	mm/day
Max Daily Drainage Volume	7.5, 6, 16, 32	mm
Bulk Density	1.6, 1.6, 1.6, 1.8	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	65	
Reducation in CN At Full Cover	5	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on but modified from Yellow Deep Sand (Buntine) has been extracted from the ASOIL State: Western Australia Region: Northern Region Nearest Town: Buntine APSOIL number: Soil Type: Yellow Deep Sand Location accuracy: Regional Soil Type Data source: YP. Collected by CSIRO as part of the GRDC SIP09 Precision Agriculture Project Comments: Birch12



A1.2.5 Deep clay loam (PAWC 250mm)

Based on Clay loam over medium clay (Quorn No605)

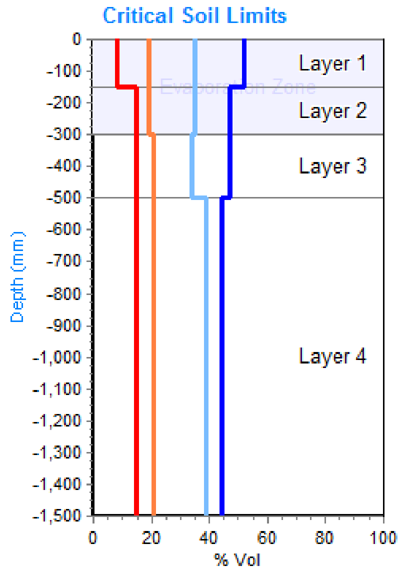
Source: APSOIL Database (CSIRO)

Original Data source: Characterisation 2008 by University of Adelaide CSIRO Sustainable Ecosystems and Rural Solutions Jamestown

Comments: LB code:QRN; David Maschmedt Description: 0-6cm Clay Loam 2.5YR 3/4; 6-45cm Medium-heavy Clay 2.5YR 3/3; 45-85cm Medium Clay 2.5YR 4/6; 85-135cm Medium Clay 2.5YR 4/8   Roots: Wheat 130cm. Moderate-high clay strongly duplex soil with moderate bulk den

Number of Horizons	4	
Layer Depths	150, 300, 500, 1500	mm
Air Dry Limit	8, 15, 15, 15	%Vol
Wilting Point	19, 19, 21, 21	%Vol
Field Capacity	35, 35, 34, 39	%Vol
Saturation Limit	52, 47, 47, 44	%Vol
PAWC	24, 24, 26, 180 (Total = 254mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 25	mm/day
Max Daily Drainage Volume	25.5, 18, 26, 50	mm
Bulk Density	1.2, 1.3, 1.3, 1.4	g/cm^3
Stage 2 Soil Evaporation, Cona	4	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	85	
Reducation in CN At Full Cover	20	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.14	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.14	(0-1)

Clay loam over medium clay (Quorn No605) has been extracted from the ASOIL Database file Soil Type: Clay loam over medium clay Data source: Characterisation 2008 by University of Adelaide CSIRO Sustainable Ecosystems and Rural Solutions Jamestown Comments: LB code: QRN; David Maschmedt Description: 0-6cm Clay Loam 2.5YR 3/4; 6-45cm Medium-heavy Clay 2.5YR 3/3; 45-85cm Medium Clay 2.5YR 4/6; 85-135cm Medium Clay 2.5YR 4/8 Roots: Wheat 130cm. Moderate-high clay strongly duplex soil with moderate bulk density.

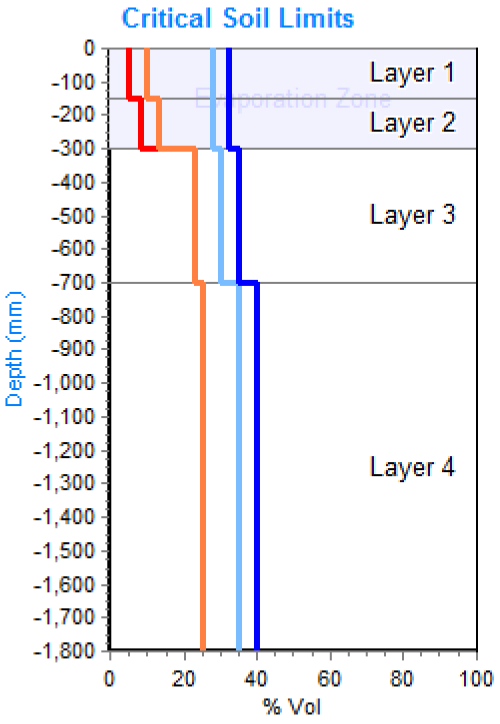


A1.2.6 Deep light clay (PAWC 185mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	150, 300, 700, 1800	mm
Air Dry Limit	5, 8, 23, 25	%Vol
Wilting Point	10, 13, 23, 25	%Vol
Field Capacity	28, 28, 30, 35	%Vol
Saturation Limit	32, 32, 35, 40	%Vol
PAWC	27, 22.5, 28, 110 (Total = 188mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 10	mm/day
Max Daily Drainage Volume	6, 6, 20, 55	mm
Bulk Density	1.3, 1.3, 1.3, 1.5	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	75	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on Heavy Red Kandosol (Greenethorpe No619-YP) has been extracted from the ASOIL Data source: YP. Made by James Hunt, BCG modified version of SW Slopes-Greenthorpe from M. Robertson & J. Kirkegaard (CSIRO PI), requested by Farmlink. CLL/AirDry data taken from SW measurements made by Tony Swan of CSIRO PI in R. Taylors Finns paddock at Greenthorpe 19 April 2007. DUL is estimated based on CLL and original soil. OC in top 1 m measured. Comments: All CLL estimated

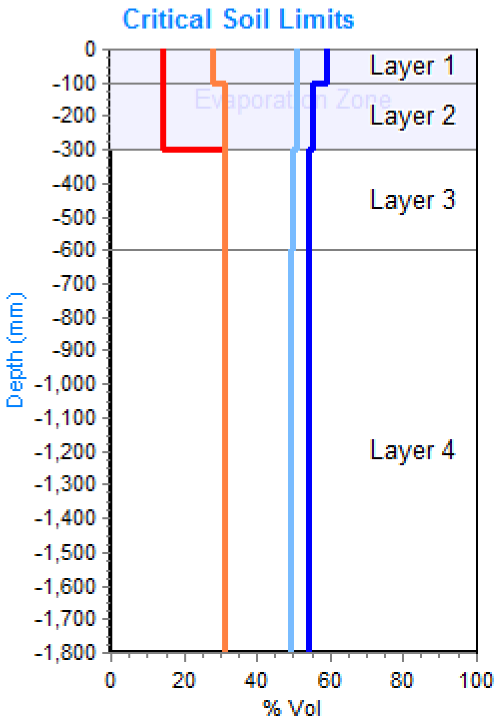


A1.2.7 Deep heavy clay (PAWC 335mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	100, 300, 600, 1800	mm
Air Dry Limit	14, 14, 31, 31	%Vol
Wilting Point	28, 31, 31, 31	%Vol
Field Capacity	51, 51, 50, 49	%Vol
Saturation Limit	59, 55, 54, 54	%Vol
PAWC	23, 40, 57, 216 (Total = 336mm)	mm
Max Daily Drainage Rate (mm/day)	100, 100, 5, 2	mm/day
Max Daily Drainage Volume	8, 8, 12, 60	mm
Bulk Density	1, 1.1, 1.2, 1.3	g/cm^3
Stage 2 Soil Evaporation, Cona	3	mm/day^0.5
Stage1 Soil Evaporation, U	5	mm
Runoff Curve Number	73	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	1	
Rainfall To Remove Roughness	1	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.14	(0-1)

Based on Black Vertosol-Irving (Greenmount No067) from ApSoil Not used in this analysis as used revised soil water from reworked LL and PWC value. Not likely to impact to any degree DMF 11102

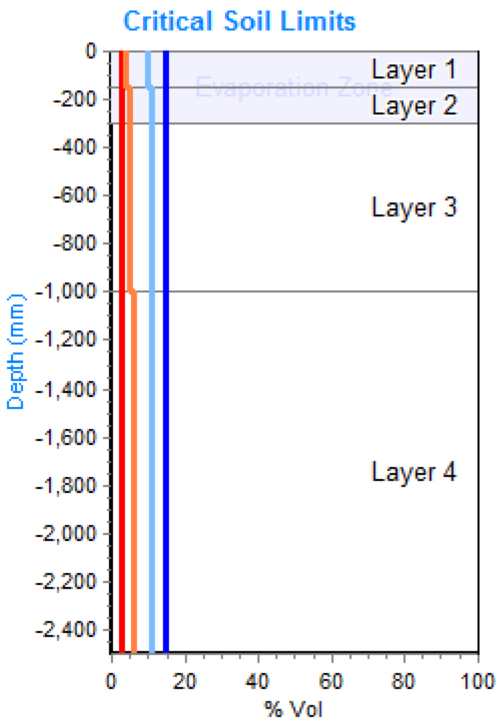


A1.2.8 Deep sand loam (PAWC 135mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	150, 300, 1000, 2500	mm
Air Dry Limit	3, 3, 3, 3	%Vol
Wilting Point	4, 5, 5, 6	%Vol
Field Capacity	10, 11, 11, 11	%Vol
Saturation Limit	15, 15, 15, 15	%Vol
PAWC	9, 9, 42, 75 (Total = 135mm)	mm
Max Daily Drainage Rate (mm/day)	50, 50, 50, 50	mm/day
Max Daily Drainage Volume	7.5, 6, 28, 60	mm
Bulk Density	1.6, 1.6, 1.6, 1.8	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	65	
Reducation in CN At Full Cover	5	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on but modified from Yellow Deep Sand (Buntine) has been extracted from the ASOIL State: Western Australia Region: Northern Region Nearest Town: Buntine APSOIL number: Soil Type: Yellow Deep Sand Location accuracy: Regional Soil Type Data source: YP. Collected by CSIRO as part of the GRDC SIP09 Precision Agriculture Project Comments: Birch12

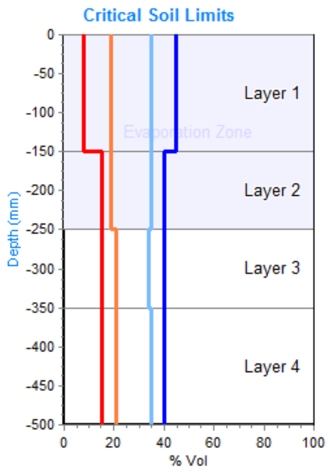


A1.2.9 Shallow clay loam (PAWC 75mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	150, 250, 350, 500	mm
Air Dry Limit	8, 15, 15, 15	%Vol
Wilting Point	19, 19, 21, 21	%Vol
Field Capacity	35, 35, 34, 35	%Vol
Saturation Limit	45, 40, 40, 40	%Vol
PAWC	24, 16, 13, 21 (Total = 74mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 25	mm/day
Max Daily Drainage Volume	15, 5, 6, 7.5	mm
Bulk Density	1.2, 1.3, 1.3, 1.4	g/cm^3
Stage 2 Soil Evaporation, Cona	4	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	85	
Reducation in CN At Full Cover	20	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	1	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.14	(0-1)

Based on but shallower than Clay loam over medium clay (Quorn No605) has been extracted from the ASOIL Database file State: South Australia Region: Flinders Nearest Town: Quorn APSOIL number: 605 Soil Type: Clay loam over medium clay Data source: Characterisation 2008 by University of Adelaide CSIRO Sustainable Ecosystems and Rural Solutions Jamestown Comments: LB code:QRN; David Maschmedt Description: 0-6cm Clay Loam 2.5YR 3/4; 6-45cm Medium-heavy Clay 2.5YR 3/3; 45-85cm Medium Clay 2.5YR 4/6; 85-135cm Medium Clay 2.5YR 4/8 Roots: Wheat 130cm. Moderate-high clay strongly duplex soil with moderate bulk density.

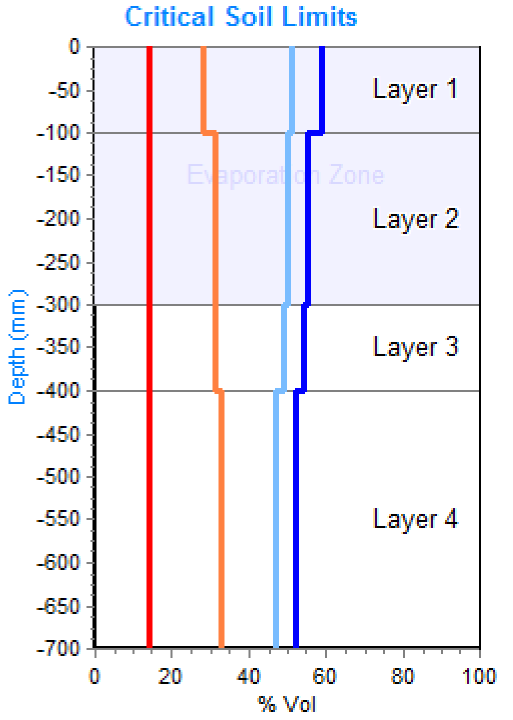


A1.2.10 Shallow heavy clay (PAWC 120mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	100, 300, 400, 700	mm
Air Dry Limit	14, 14, 14, 14	%Vol
Wilting Point	28, 31, 31, 33	%Vol
Field Capacity	51, 50, 49, 47	%Vol
Saturation Limit	59, 55, 54, 52	%Vol
PAWC	23, 38, 18, 42 (Total = 121mm)	mm
Max Daily Drainage Rate (mm/day)	100, 100, 5, 2	mm/day
Max Daily Drainage Volume	8, 10, 5, 15	mm
Bulk Density	1, 1.1, 1.2, 1.3	g/cm^3
Stage 2 Soil Evaporation, Cona	3	mm/day^0.5
Stage1 Soil Evaporation, U	5	mm
Runoff Curve Number	73	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	1	
Rainfall To Remove Roughness	1	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks		mm
Sediment Delivery Ratio	0.14	(0-1)

Black Vertosol-Irving (Greenmount No067) from ApSoil. Not used in this analysis as used revised soil water from reworked LL and PWC values. Not likely to impact to any degree DMF 111021

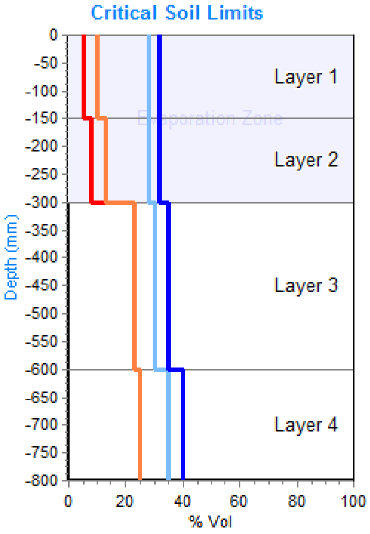


A1.2.11 Shallow light clay (PAWC 90mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	150, 300, 600, 800	mm
Air Dry Limit	5, 8, 23, 25	%Vol
Wilting Point	10, 13, 23, 25	%Vol
Field Capacity	28, 28, 30, 35	%Vol
Saturation Limit	32, 32, 35, 40	%Vol
PAWC	27, 22.5, 21, 20 (Total = 91mm)	mm
Max Daily Drainage Rate (mm/day)	100, 50, 25, 10	mm/day
Max Daily Drainage Volume	6, 6, 15, 10	mm
Bulk Density	1.3, 1.3, 1.3, 1.5	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5	mm/day^0.5
Stage1 Soil Evaporation, U	6	mm
Runoff Curve Number	75	
Reducation in CN At Full Cover	10	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on Heavy Red Kandosol (Greenethorpe No619-YP) has been extracted from the ASOIL Data source: YP. Made by James Hunt, BCG modified version of SW Slopes-Greenthorpe from M. Robertson & J. Kirkegaard (CSIRO PI), requested by Farmlink. CLL/AirDry data taken from SW measurements made by Tony Swan of CSIRO PI in R. Taylors Finns paddock at Greenthorpe 19 April 2007. DUL is estimated based on CLL and original soil. OC in top 1 m measured. Comments: All CLL estimated

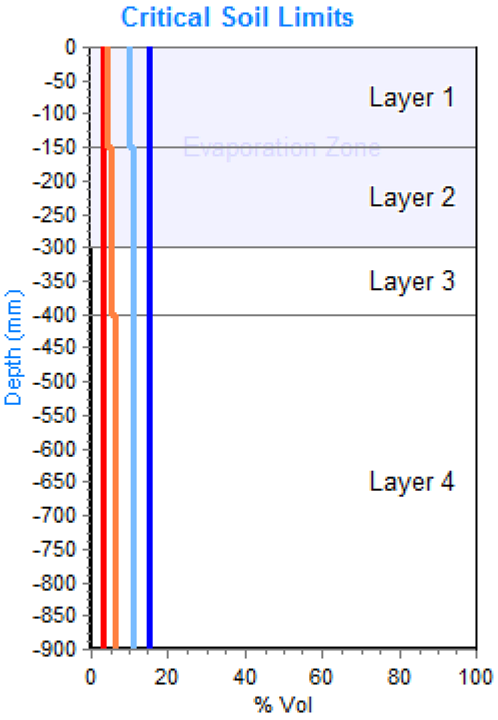


A1.2.12 Shallow sand loam (PAWC 50mm)

Source: APSOIL Database (CSIRO)

Number of Horizons	4	
Layer Depths	150, 300, 400, 900	mm
Air Dry Limit	3, 3, 3, 3	%Vol
Wilting Point	4, 5, 5, 6	%Vol
Field Capacity	10, 11, 11, 11	%Vol
Saturation Limit	15, 15, 15, 15	%Vol
PAWC	9, 9, 6, 25 (Total = 49mm)	mm
Max Daily Drainage Rate (mm/day)	100, 100, 100, 50	mm/day
Max Daily Drainage Volume	7.5, 6, 4, 20	mm
Bulk Density	1, 1.2, 1.6, 1.8	g/cm^3
Stage 2 Soil Evaporation, Cona	3.5 Yunusa et al AJSR 1994	mm/day^0.5
Stage1 Soil Evaporation, U	6 Yunusa et al AJSR 1994	mm
Runoff Curve Number	65	
Reducation in CN At Full Cover	5	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.4	metric
USLE P	1	
Field Slope	9	%
Slope Length	22	m
Rill Ratio	0.5	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	0	mm
Sediment Delivery Ratio	0.15	(0-1)

Based on but modified from Yellow Deep Sand (Buntine) has been extracted from the ASOIL State: Western Australia Region: Northern Region Nearest Town: Buntine APSOIL number: Soil Type: Yellow Deep Sand Location accuracy: Regional Soil Type Data source: YP. Collected by CSIRO as part of the GRDC SIP09 Precision Agriculture Project Comments: Birch12

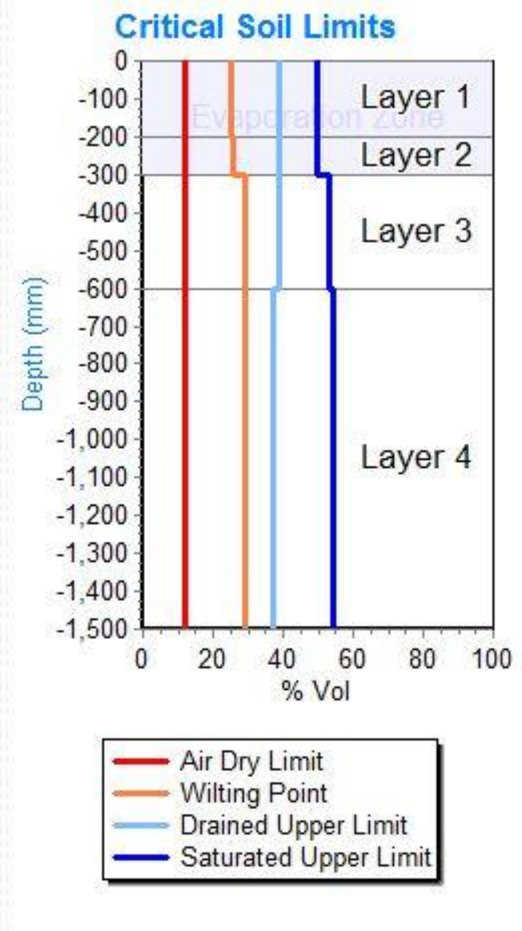


A1.2.13 Ferrosol Kairi Research Station

Source: Howleaky Installation (RPS)

Number of Horizons	4	
Layer Depths	200, 300, 600, 1500	mm
Air Dry Limit	12, 12, 12, 12	%Vol
Wilting Point	25, 26, 29, 29	%Vol
Field Capacity	39, 39, 39, 37	%Vol
Saturation Limit	50, 50, 53, 54	%Vol
PAWC	28, 13, 30, 72 (Total = 143mm)	mm
Max Daily Drainage Rate (mm/day)	200, 200, 100, 100	mm/day
Max Daily Drainage Volume	22, 11, 42, 153	mm
Bulk Density	1.2, 1.4, 1.5, 1.5	g/cm^3
Stage 2 Soil Evaporation, Cona	8	mm/day^0.5
Stage1 Soil Evaporation, U	0	mm
Runoff Curve Number	75	
Reducation in CN At Full Cover	30	
Max. Reduction In CN Due To Till	0	
Rainfall To Remove Roughness	0	mm
USLE K	0.9	metric
USLE P	1	
Field Slope	5	%
Slope Length	20	m
Rill Ratio	1	(0-1)
Simulate Soil Cracking	false	
Max. Infiltration Into Cracks	15	mm
Sediment Delivery Ratio	0.1	(0-1)

Generic deep Ferrosol (1500mm) of the Atherton Tablelands with medium to high clay content. Description based on details in Cogle et al. (2011). PAWC 143 mm.



Appendix 2 - LAI vegetation input parameters

A2.1 Parameter descriptions

Input parameter	Description

Potential max LAI (cm^2/cm^2)
Name in file:
`PotMaxLai`
Name in code:
`PotMaxLAI`
	The upper limit of the leaf area index (LAI) - development curve.
	Range: 1 to 10
	Suggested Values: 2 to 4 for most dryland crops, 5 to 8 for irrigated, high input crops.

Prop. season for max LAI (fraction)
Name in file:
`PropGrowSeaForMaxLai`
Name in code:
`PropSeasonForMaxLAI`
	The development stage for potential maximum LAI.
	Range: 0 to 1
	Suggested Values: 0.4 to 0.6 for crops with early leaf development and long leaf persistence (eg sorghum). 0.65 to 0.8 for crops with slower leaf area development and rapid senescence (e.g. wheat)

Prop. max LAI (1st) (%)
Name in file:
`PercentOfMaxLai1`
Name in code:
`LAICurveY1`
	LAI for the 1st development stage.
	Range: 0 to 100
	Suggested Values: none available

Prop. grow-season (1st) (%)
Name in file:
`PercentOfGrowSeason1`
Name in code:
`LAICurveX1`
	The development stage for the 1st LAI "point".
	Range: 0 to 100
	Suggested Values: none available

Prop. max LAI (2nd) (%)
Name in file:
`PercentOfMaxLai2`
Name in code:
`LAICurveY2`
	LAI for the 2nd development stage.
	Range: 0 to 100
	Suggested Values: none available

Prop. grow-season (2nd) (%)
Name in file:
`PercentOfGrowSeason2`
Name in code:
`LAICurveX2`
	The development stage for the 2nd LAI "point".
	Range: 0 to 100
	Suggested Values: none available

SW prop for no crop stress (0-1) **Name in file:** `SWPropForNoStress` **Name in code:** `SWPropForNoStress`	Proportion of Soil Water Volume for which transpiration is not limited. **Range:** 0 to 1 **Suggested Values**: Previous default value was 0.3 - some crops might go as high as 0.8.

Degree days plant-harvest (oC)
Name in file:
`DegreeDaysPlantToHarvest`
Name in code:
`DegreeDaysToMaturity`
	The sum of degree-days (temperature less the base temperature) between planting and harvest. Controls the rate of crop development and the potential duration of the crop. Some plants develop to maturity and harvest more slowly than others - these accumulate more degree-days between plant and harvest.
	Range: 1 to 10000
	Suggested Values: From about 1000 for very quick crops to 3000 for slow ones. Can be set to several thousand to simulate biennial or short-lived perennials.

Senesence coefficient
Name in file:
`SenesenceCoef`
Name in code:
`SenesenceCoefficient`
	Rate of LAI decline after max LAI.
	Range: 0.01 to 5
	Suggested Values: For slow senescence, from 0.1 to 0.5, and for rapid senescence, from 0.5 to 2.

Radiation use efficiency (g/m^2/MJ)
Name in file:
`RadUseEffic`
Name in code:
`RadiationUseEfficiency`
	Biomass production per unit of radiation.
	Range: 0.1 to 10
	Suggested Values: 1.5 to 2.5 g/MJ in crops with the C3 metabolic pathway (wheat etc.), and 2 to 3 g/MJ in C4 crops (sorghum, rice etc.)

Harvest index **Name in file:** `HarvestIndex` **Name in code:** `HarvestIndex`	The grain biomass (kg/ha) divided by the above-ground biomass at flowering (kg/ha) **Range**: 0.1 to 5 **Suggested Values:** Most crops range from 0.2 to 0.6, with lower values occurring in energy or protein-dense products. Typical canola = 0.3, wheat = 0.42, sorghum = 0.5, rice = 0.5
Base temperature (oC) **Name in file:** `BaseTemp` **Name in code:** `BaseTemp`	The lower limit of plant development and growth, with respect to temperature (the average day temperature, degrees Celsius). The base temperature of vegetation is dependent on the type of environment in which the plant has evolved, and any breeding for hot or cold conditions. **Range**: -5 to 20 **Suggested Values:** Recommended base temperatures are 0 C for "temperate" crops such as wheat, and 8 to 14 C for "tropical" crops, such as sorghum, maize and cotton. Some cold-tolerant subtropical (C4) grasses and heat-tolerant tropical (C3) tree species have intermediate base temperatures (e.g. 6 to 8 C for kikuyu).

Optimal temperature (oC)
Name in file:
`OptTemp`
Name in code:
`OptimalTemp`
	The temperature for maximum biomass production. Biomass production is a linear function of temperature between the Base temperature and the Optimum temperature.
	Range: 0 to 40
	Suggested Values: Approximately 20 C for wheat and temperate species, 30 C for tropical species.

Maximum root depth (mm)
Name in file:
`MaxRootDepth`
Name in code:
`MaximumRootDepth`
	The maximum depth of the roots from the soil surface. For the LAI model, the model calculates daily root growth from the root depth increase parameter.
	Range: 1 to 10000
	Suggested Values: Ensure that the soil depth specified by "Layer Depth (Cumulative)" is greater than the Maximum root depth â€“ the model will use the minimum of the two values.

Daily root growth (mm) **Name in file:** `DailyRootGrowth` **Name in code:** `DailyRootGrowth`	The daily increment in root depth. **Range**: 0 to 100 **Suggested Values:** For crops this is often about 20 mm/day.

Water stress threshold (0-1)
Name in file:
`WatStressForDeath`
Name in code:
`WaterStressThreshold`
	Ratio of water supply to potential water supply that indicates a stress day
	Range: 0 to 1
	Suggested Values: none available

Stress days to death (days)
Name in file:
`DaysOfStressToDeath`
Name in code:
`StressDaysToDeath`
	The number of consecutive days that water supply is less than threshold before the crop is killed.
	Range: 1 to 1000
	Suggested Values: from 10 to 30 days.

Residue decomposition rate (%/day)
Name in file:
`MaxResidueLoss`
Name in code:
`DecompositionRate`
	Residue decomposition rate (%/day)
	The rate of removal of plant residues from the soil surface by decay. Fraction of current plant/crop residues that decay each day. Plant residues on the soil surface are used in calculation of soil evaporation, runoff and erosion.
	Range: 0.1 to 20
	Suggested Values: 0.01 is often a useful starting value (1% of residues decay each day).

Residue at full cover (kg/ha) **Name in file:** `BiomassAtFullCover` **Name in code:** `BiomassAtFullCover`	The amount of dry plant residues (i.e. stubble, pasture litter etc) that results in complete coverage of the ground. This parameter controls the relationship between the amount of crop residue and cover, which is used in calculating runoff and erosion. **Range**: 0 to 10000 **Suggested Values:** 5000 for wheat and barley crop residues (usually 4,000 to 15,000 kg/ha)

Prop. GGD to end irrigation (%)
Name in file:
`PropGGDEnd`
Name in code:
`PropGDDtoEnd`
	Set the proportion of the growth cycle for which irrigation is possible.
	Range: 1 to 100
	Suggested Values: not available

Planting scheduling
Name in file:
`PlantingFormat`
Name in code:
`PlantingRules`
	Option to define how crops are planted. The “Automatic” option is based on a range of input conditions that must be met before a crop will plant. “Fixed date” will plant the crop on the same date each year. “Sequence” allows the user to define all planting dates in a simulation.
	Range: “Automatic”, “Fixed date (Annual)” or “Sequence”
	Suggested Values: Fixed date is the simplest.

Start of planting window
Visible when using the “Automatic” planting scheduling option.
Name in file:
`StartPlantWindow`
Name in code:
`PlantWindowStartDay,`
`PlantWindowStartMonth`
	Define the first day and month where cropping is possible using the “Automatic” planting scheduling option.
	Range: 1 Jan to Dec 31
	Suggested Values: Depends on crop

End of planting window
Visible when using the “Automatic” planting scheduling option.
Name in file:
`EndPlantWindow`
Name in code:
`PlantWindowEndDay,`
`PlantWindowEndMonth`
	Define the last day and month where cropping is possible using the “Automatic” planting scheduling option.
	Range: 1 Jan to Dec 31
	Suggested Values: Depends on crop

Planting date
Visible when using the “Fixed date” planting scheduling option.
Name in file:
`PlantDate`
Name in code:
`FixedPlantDay`
	Define the day and month when crops will be planted each year using the “Fixed date” planting scheduling option.
	Range: 1 Jan to Dec 31
	Suggested Values: Depends on crop

Force planting in window
Visible when using the "Automatic" planting scheduling option.
Name in file:
`ForcePlanting`
Name in code:
`ForcePlantingAtEndOfWindow`
	Force planting in window is used when "Automatic" planting scheduling is selected to ensure that a crop is planted at the end of the "window", even if all the conditions weren't met.
	Range: YES or NO
	Suggested Values: NO

Can plant multiple times in windows *Visible when using the "Automatic" planting scheduling option.* **Name in file:** `MultiPlantInWindow` **Name in code:** `MultiPlantInWindow`	Allows crops to be planted multiple times in any planting "window". **Range**: YES or NO **Suggested Values**: NO
Rotation options *Visible when using the "Automatic" or "Fixed Date" planting scheduling option.* **Name in file:** RotationOptions **Name in code:** `RotationOptions`	The "Rotation Options" parameter allows you to define how multiple crops can be ordered. For this to be of use, multiple LAI-based crops must be included in the simulation. The "uncontrolled" option will try to plant another crop if the first crop fails to plant. There are no additional rules applied to this. The "opportunity" option extends the "uncontrolled" option by providing addition rules pertaining to the minimum and maximum allowable rotation of this crop that must be met, along with a minimum period between these rotations. The "In crop Order" option extends the "opportunity" option be ensuring that crops must be planted in the same order they are included in the simulation. This could mean that crops could occasionally fail to plant if conditions are met. **Range**: "Uncontrolled", "Opportunity" or "Fixed Order" **Suggested Values**: None provided

Attempt to plant at least this many seasons in a row
Visible when using the "Automatic" or "Fixed Date" planting scheduling option, and "Opportunity" or "In crop order" are selected in the rotation options.
Name in file:
`MinContinuousRotations`
Name in code:
`MinRotationCount`
	One of the criteria used when testing if a crop can be replanted, or if another crop should be tested. Represents the minimum number of continuous plantings of this crop in a row.
	Range: 0 to 10000000
	Suggested Values: None provide

Dont plant more than this many seasons in a row
Visible when using the "Automatic" or "Fixed Date" planting scheduling option, and "Opportunity" or "In crop order" are selected in the rotation options.
Name in file:
`MaxContinuousRotations`
Name in code:
`MaxRotationCount`
	One of the criteria used when testing if a crop can be replanted, or if another crop should be tested. Represents the maximum number of continuous plantings of this crop in a row.
	Range: 0 to 10000000
	Suggested Values: None provide

Min rest period between continuous rotations of this crop
Visible when using the "Automatic" or "Fixed Date" planting scheduling option, and "Opportunity" or "In crop order" are selected in the rotation options.
Name in file:
`MinYearsBetweenSowing`
Name in code:
`RestPeriodAfterChangingCrops`
	Minimum number of days between sowing this crop. e.g. chickpeas might have a minimum of 4 years (1460 days) between sowing, so that if they are sown in 2002 they can't be sown in 03 04 or 05.
	Range: 0 to 999999999
	Suggested Values: no suggestions

Planting dates
Visible when using the "Sequence" planting scheduling option
Name in file:
`PlantingDates`
Name in code:
`XXXX`
	List of planting dates (in **dd/mm/yyyy**) format separated by a comma. During a simulation, planting will be forced to occur on these dates so long as they are within the period of the simulation start and end dates.
	Range: Climate data range and simulation start and end dates.
	Suggested Values: Provide at least one for each year.

Test fallow conditions *Visible when using the "Automatic" planting scheduling option* **Name in file:** `FallowSwitch` **Name in code:** `FallowSwitch`	Checks whether a minimum fallow period must exist before planting the crop. Used in "Automatic" planting scheduling options. **Range**: YES or NO **Suggested Values**: no suggestions
Minimum fallow length (days) *Visible when using the "Automatic" planting scheduling option, along with "Test Fallow Conditions" set to YES.* **Name in file:** **MinFallowLength** **Name in code:** `MinimumFallowPeriod`	Minimum number of fallows days which much occur before a crop can be planted/replanted. **Range**: 1 to 10000 **Suggested Values**: no suggestions

Test rainfall conditions
Visible when using the "Automatic" planting scheduling option
Name in file:
`RainfallSwitch`
Name in code:
`PlantingRainSwitch`
	Checks whether a minimum fallow period must exist before planting the crop. Used in "Automatic" planting scheduling options.
	Range: YES or NO
	Suggested Values: no suggestions:

Planting rain (mm)
Visible when using the "Automatic" planting scheduling option, along with "Test Rainfall Conditions" set to YES.
Name in file:
`PlantingRain`
Name in code:
`RainfallPlantingThreshold`
	Minimum rainfall amount which much occur before a crop can be planted/replanted. Used in conjunction with "Days to summate rain".
	Range: 1 to 10000
	Suggested Values: no suggestions

Days to summate rain
Visible when using the "Automatic" planting scheduling option, along with "Test Rainfall Conditions" set to YES.
Name in file:
`DaysToTotalRain`
Name in code:
`RainfallSummationDays`
	Number of days to summate rainfall to test rainfall conditions for planting. Used in conjunction with "Planting rain".
	Range: 1 to 10000
	Suggested Values: no suggestions

Sowing delay *Visible when using the "Automatic" planting scheduling option, along with "Test Rainfall Conditions" set to YES.* **Name in file:** `SowingDelay` **Name in code:** `SowingDelay`	Number of rain-free days AFTER the sowing rules are met. **Range**: 0 to 100 **Suggested Values**: no suggestions

Test soil water conditions
Visible when using the "Automatic" planting scheduling option.
Name in file:
`SoilWaterSwitch`
Name in code:
`FallowSwitch`
	Checks to see if soil-water conditions are suitable for planting the crop. Used in "Automatic" planting scheduling options.
	Range: YES or NO
	Suggested Values: no suggestions

Min soil water ratio (layer 1) (0-1)
Visible when using the "Automatic" planting scheduling option, along with "Test Soil Water Conditions" set to YES.
Name in file:
`MinSoilWaterRatio`
Name in code:
`MinSoilWaterTopLayer`
	Minimum soil water conditions (ratio) in layer 1 that must be met before planting can be considered.
	Range: 0 to 1
	Suggested Values: no suggestions

Max soil water ratio (layer 1) (0-1)
Visible when using the "Automatic" planting scheduling option, along with "Test Soil Water Conditions" set to YES.
Name in file:
`MaxSoilWaterRatio`
Name in code:
`MaxSoilWaterTopLayer`
	Maximum soil water conditions (ratio) in layer 1 that must be met before planting can be considered.
	Range: 0 to 1
	Suggested Values: no suggestions

Minimum available soil water at planting (mm)
Visible when using the "Automatic" planting scheduling option, along with "Test Soil Water Conditions" set to YES.
Name in file:
`AvailSWAtPlanting`
Name in code:
`SoilWaterReqToPlant`
	Minimum available soil water (mm) (to a defined depth- see next parameter) that must exist before planting can be considered. Used in conjunction with "Soil depth to sum planting soil water".
	Range: 0.1 to 300
	Suggested Values: no suggestions

Soil depth to sum planting soil water (mm)
Visible when using the "Automatic" planting scheduling option, along with "Test Soil Water Conditions" set to YES.
Name in file:
`SoilDepthToSumPlantingSW`
Name in code:
`DepthToSumPlantingWater`
	Depth of soil to summate soil water when checking soil water conditions for planting. Used in conjunction with "Minimum available soil water at planting".
	Range: 50 to 10000
	Suggested Values:

Ratoon crop
Visible when using the "Automatic" or "Fixed date" planting scheduling option.
Name in file:
`RatoonCrop`
Name in code:
`Ratooning`
	Used to activate multiple harvest or ratoon sequences for crops such as sugar cane or lucerne. This functionality is inherited from the ***PERFECT*** code and may not function as intended when combined with the additional HowLeaky planting rules.
	Range: YES or NO
	Suggested Values: NO!! NOT RECOMMENDED

Number of ratoons
Visible when using the "Automatic" or "Fixed date" planting scheduling option, along with "Ratoon" set to YES.
Name in file:
`RatoonCount`
Name in code:
`NumberOfRatoons`
	Number of ratoons in the ratooning sequence.
	Range: 0 to 1000
	Suggested Values: NOT RECOMMENDED

Ratoon scaling factor (0-1)
Visible when using the "Automatic" or "Fixed date" planting scheduling option, along with "Ratoon" set to YES.
Name in file:
`RatoonScaleFactor`
Name in code:
`ScalingFactorForRatoons`
	Reduction in above-ground biomass and cover that occurs at harvest. Root depth is not affected.
	Range: 0 to 1
	Suggested Values: NOT RECOMMENDED

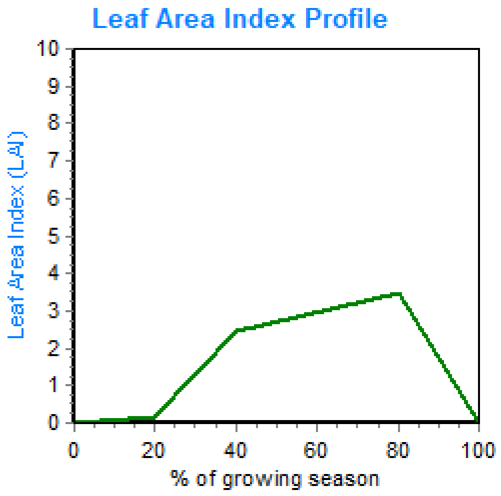
Waterlogging **Name in file:** `Waterlogging` **Name in code:** `Waterlogging`	Waterlogging option is used to stress transpiration and biomass production. When the soil is waterlogged; (a) potential transpiration is reduced (scaled) by the WaterLoggingFactor1; and (b) the effective radiation use efficiency is reduced (scaled) by the WaterLoggingFactor2. **Range**: 0 to 1 **Suggested Values**: depends on crop variety
WaterLoggingFactor1 (0-1) *Visible when using the "WaterLogging" option* **Name in file:** `WaterLoggingFactor1` **Name in code:** `WaterLoggingFactor1`	The amount which potential transpiration is reduced (scaled) when the soil is waterlogged. **Range**: 0 to 1 **Suggested Values**: depends on crop variety

WaterLoggingFactor2 (0-1)
Visible when using the "WaterLogging" option
Name in file:
`WaterLoggingFactor2`
Name in code:
`WaterLoggineFactor2`
	The amount which biomass production is reduced (scaled) when the soil is waterlogged.
	Range: 0 to 1
	Suggested Values: depends on crop variety

A2.2 Sample LAI parameter values

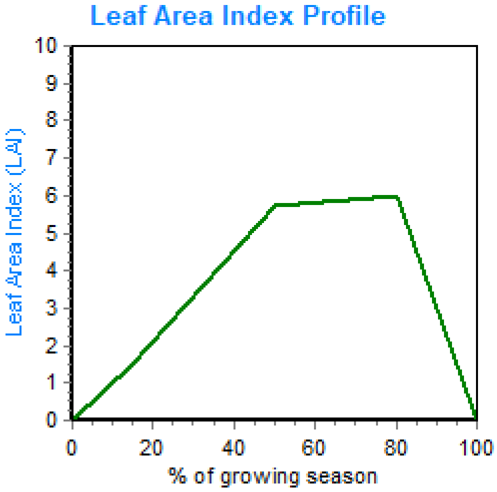
A2.2.1 Cotton Dalby

Name	CurrentValue
Potential max LAI	3.5 cm^2/cm^2
Prop. season for max LAI	0.8 fraction
Prop. max LAI (1st)	5 %
Prop. grow-season (1st)	20 %
Prop. max LAI (2nd)	70 %
Prop. grow-season (2nd)	40 %
Degree days plant-harvest	2100 oC
Senesence coefficient	0.2
Radiation use efficiency	2 g/m^2/MJ
Harvest index	0.1 This is an approximate figure, based on 8 to 9 bales (1100 kg) per 700mm of Et (Tennakoon and Milroy)
Base temperature	10 oC
Optimal temperature	32 oC
Maximum root depth	900 mm
Daily root growth	15 mm
Water stress threshold	0.1 (0-1)
Stress days to death	21 days
Residue decomposition rate	5 %/day
Residue at full cover	10000 kg/ha
Prop. GGD to end irrigation	75 %
Planting scheduling	Fixed Date (annual)
Planting date	7 Oct
Rotation options	Uncontrolled
Ratoon crop	No



A2.2.2 SORGHUM quick

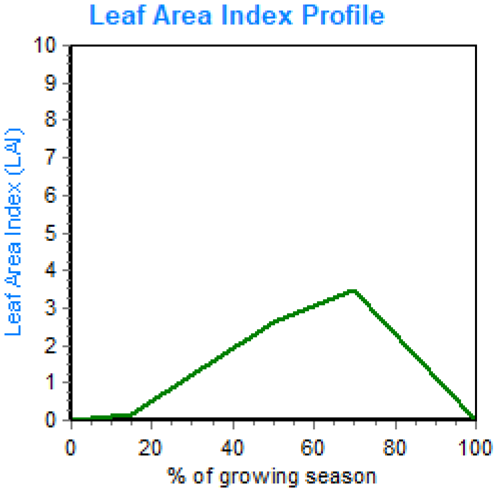
Name	CurrentValue
Potential max LAI	6 cm^2/cm^2
Prop. season for max LAI	0.8 fraction
Prop. max LAI (1st)	25 %
Prop. grow-season (1st)	15 %
Prop. max LAI (2nd)	95 %
Prop. grow-season (2nd)	50 %
Degree days plant-harvest	1750 oC
Senesence coefficient	0.2
Radiation use efficiency	2.4 g/m^2/MJ
Harvest index	0.4
Base temperature	11 oC
Optimal temperature	30 oC
Maximum root depth	1500 mm
Daily root growth	15 mm
Water stress threshold	0.2 (0-1)
Stress days to death	21 days
Residue decomposition rate	5 %/day
Residue at full cover	5000 kg/ha
Prop. GGD to end irrigation	80 %
Planting scheduling	Automatic
Start of planting window	15 Oct
End of planting window	28 Jan
Force planting in window	No
Can plant mulitiple times in windows	No
Rotation options	Uncontrolled
Test fallow conditions	No
Test rainfall conditions	No
Test soil water conditions	No
Ratoon crop	No



A2.2.3 Wheat - quick

C:\Program Files (x86)\HowLeaky\Data - Vegetation\Sample - Wheat quick.vege

Name	CurrentValue
Potential max LAI	3.5 cm^2/cm^2 MAX LAI: Doyle and Fischer AJAR 1979 Tamworth = 2.8 Sudmeyer et al AJEA 2002 Rutherglen = 4.1 Warwick = 1.7, Esperence = 3.4 Sloane et al AJAR 2004 2 years high density, Roseworthy = 1.87, Kapunda = 2.74
Prop. season for max LAI	0.7 fraction
Prop. max LAI (1st)	5 %
Prop. grow-season (1st)	15 %
Prop. max LAI (2nd)	75 %
Prop. grow-season (2nd)	50 %
Degree days plant-harvest	1900 oC Doyle and Fischer AJAR 1979 quote 1650 for Tamworth for sowing to 4t/ha DM. Assuming 4t/ha is 0.75 of harvest GDD, GDD = 2000 for Timgalen.
Senesence coefficient	0.75 Moderate senescence post anthesis. Approx 4 -5 weeks (as per Doyle and Fischer AJAR 1979)
Radiation use efficiency	2.4 g/m^2/MJ Values in Purcell et al Crop Science 2002 range mostly from 1.3 to 1.6 g/MJ PAR
Harvest index	0.42 Modern semi-dwarfs range from 0.38 to 0.45
Base temperature	0 oC
Optimal temperature	20 oC
Maximum root depth	1200 mm
Daily root growth	15 mm
Water stress threshold	0.1 (0-1)
Stress days to death	21 days
Residue decomposition rate	4 %/day
Residue at full cover	5000 kg/ha
Prop. GGD to end irrigation	1 %
Planting scheduling	Automatic
Start of planting window	1 May
End of planting window	14 Jul
Force planting in window	No
Can plant mulitiple times in windows	No
Rotation options	Uncontrolled
Test fallow conditions	No
Test rainfall conditions	No
Test soil water conditions	No
Ratoon crop	No



Appendix 3 - Cover vegetation model

A3.1 Parameter Descriptions

Plant day (Julian days) **Name in file:** `PlantDay` **Name in code:** `PlantDay`	Plant day in Julian days. Unfortunately, ***HowLeaky*** does not estimate this from the crop cover profile and you must add in manually if you wish to calculate yield. **Range:** 1 to 365 days **Suggested Values:** Depends on crop
Days from planting to harvest (days) **Name in file:** `DaysFromPlaningToHarvest` **Name in code:** `DaysFromPlaningToHarvest`	Number of days from planting to harvest. Unfortunately, ***HowLeaky*** does not estimate this from the crop cover profile and you must add in manually if you wish to calculate yield. **Range:** 1 to 1000000 days **Suggested Values:** from 100 days for a quick crop to 50 years or longer (18, 250 days) for a plantation.
SW prop for no crop stress (0-1) **Name in file:** `SWPropForNoStress` **Name in code:** `SWPropForNoStress`	Proportion of Soil Water Volume for which transpiration is not limited. **Range:** 0 to 1 **Suggested Values**: Previous default value was 0.3 - some crops might go as high as 0.8.
Cover Input Options **Name in file:** `CoverDataType` **Name in code:** `CoverDataType`	Select whether the cover profiles are entered by hand (User-defined) or linked to a time-series datafile. **Range:** “User-defined” or “From data file” **Suggested Values:** “user-defined” – “From data file” is meant for ***DairyMod*** users.

Green Cover (Residue Cover and Root Depth)
Visible when “Cover Input Options” is set to “User-Defined”.
Name in file:
`CropFactorMatrix (Data, x, y, z, a)`
Name in code:
`GreenCoverData,`
`ResidueCoverData,`
`RootDepthData`
	This parameter is called “Green Cover” in the user interface but is actually linked to “Green Cover (%)”, “Residue Cover (%)” and “Root Depth (mm)”. Each set of data must be associated with a unique day number (Julian days).
	Range: 0-100% for cover, 0 to 1000000mm for root depth.
	Suggested Values: Depends on crop

Source Data *Visible when “Cover Input Options” is set to “From data-file”.* **Name in file:** `SourceData` **Name in code:** `SourceData`	Target data-file name for file containing the green biomass, residue biomass and root biomass time-series. You can link to an already imported time-series file or you can import a new file through the “From data file” option. **Range:** Select a data file **Suggested Values:** none
Green Biomass Time-series *Visible when “Cover Input Options” is set to “From data-file”.* **Name in file:** `GreenCoverTimeSeries` **Name in code:** `GreenCoverTimeSeries`	Name of the **green** biomass time series listed in the data file selected in “Source Data”. **Range:** HowLeaky will list available time series for you to select. **Suggested Values:** Pick the **green** biomass one.

Residue Biomass Time-series *Visible when "Cover Input Options" is set to "From data-file".* **Name in file:** `ResidueCoverTimeSeries` **Name in code:** `ResidueCoverTimeSeries`	Name of the **residue** biomass time series listed in the data file selected in "Source Data". **Range:** HowLeaky will list available time series for you to select. **Suggested Values:** Pick the **residue** biomass one.
Root Biomass Time-series *Visible when "Cover Input Options" is set to "From data-file".* **Name in file:** `RootDepthTimeSeries` **Name in code:** `RootDepthTimeSeries`	Name of the **root** biomass time series listed in the data file selected in "Source Data". **Range:** HowLeaky will list available time series for you to select. **Suggested Values:** Pick the **root** biomass one.

Transpiration efficiency (kg/ha/mm trans)
Name in file:
`WaterUseEffic`
Name in code:
`WaterUserEfficiency`
	Used to estimate dry matter from transpiration. The ratio of grain production (kg/ha) to water supply (mm).
	Range: 0.1 to 1000
	Suggested Values: Usually in the range 5 to 20 kg/ha/mm. Larger values indicate more efficient water use.

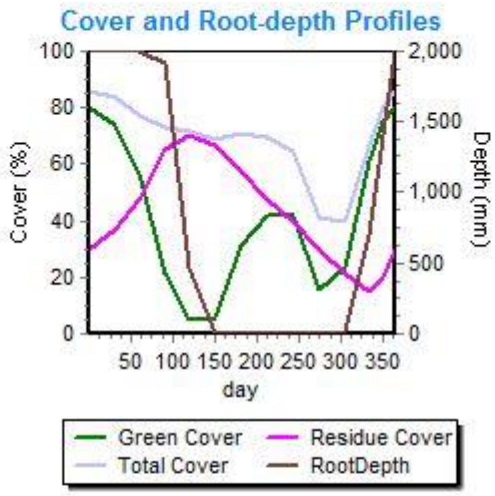
Harvest index
Name in file:
`PanHarvestIndex`
Name in code:
`HarvestIndex`
	The grain biomass (kg/ha) divided by the above-ground biomass at flowering (kg/ha). Used to convert dry matter into yield.
	Range: 0.1 to 5
	Suggested Values: most crops range from 0.2 to 0.6, with lower values occurring in energy or protein-dense products. Typical canola = 0.3, wheat = 0.42, sorghum = 0.5, rice = 0.5

Green Cover Multiplier/Conversion Factor **Name in file:** `GreenBioConvert` **Name in code:** `GreenBioConvert`	A scaling factor which will be used to scale all green cover data. This parameter has a dual purpose. When "Cover Input Options" are set to "user-defined", it is a linear scaling (calibration/adjustment factor). When set to "From data file", it is a conversion factor to convert green biomass (kg/ha) into % cover. **Range:** positive number. **Suggested values:** When dealing with cover, this value will be close to 1. When dealing with biomass, it will be equal to whatever is required to convert biomass to %cover.
Residue Cover Multiplier/Conversion Factor **Name in file:** `ResidueBioConvert` **Name in code:** `ResidueBioConvert`	A scaling factor which will be used to scale all residue cover data. This parameter has a dual purpose. When "Cover Input Options" are set to "user-defined", it is a linear scaling (calibration /adjustment factor). When set to "From data file", it is a conversion factor to convert green biomass (kg/ha) into % cover. **Range:** positive number. **Suggested values:** When dealing with cover, this value will be close to 1. When dealing with biomass, it will be equal to whatever is required to convert biomass to %cover.
Root DepthMultiplier/Conversion Factor **Name in file:** `RootBioConvert` **Name in code:** `RootBioConvert`	A scaling factor which will be used to scale all root depth data. This parameter has a dual purpose. When "Cover Input Options" are set to "user-defined", it is a linear scaling (calibration/adjustment factor). When set to "From data file", it is a conversion factor to convert root biomass (kg/ha) into root depth. **Range:** positive number. **Suggested values:** When dealing with cover, this value will be close to 1. When dealing with biomass, it will be equal to whatever is required to convert biomass to %cover.

A3.2 Sample Parameter Files

Opportunity crop No till

Cover Input Option	User-defined	
Crop-Factor Data Count	14	
Pan Plant Day	1	
Planting To Harvest	10000	days
Green Cover Multiplier	1	
Reside Cover Multiplier	1	
Root Depth Multiplier	1	
Transpiration Efficiency	0.1	kg/ha/mm trans
Pan Harvest Index	0.35	



Appendix 4 – Tillage input parameters

<table>
<tr><th></th><th></th></tr>
<tr><td>Tillage format

Name in file:
<code>TillageFormat</code>
Name in code:
<code>TillageFormat</code></td><td>Tillage format is a scheduling option with 11 different alternatives. This includes automatic (based on conditions), fixed date, at crop planting, at crop harvest, and through a sequence file.
Range: “Automatic”, “Fixed Dates (annual)”, “At Planting (All Crops)”, “At Planting (Crop 1)”, “At Planting (Crop 2)”, “At Planting (Crop 3)”, “At Harvest (All Crops)”, “At Harvest (Crop 1)”, “At Harvest (Crop 2)”, “At Harvest (Crop 3)”, “Sequence”.
Suggested Values: Depends on your scenario. You can add many tillage events into a scenario, so within a simulation, you can customise a range of fallow, planting and harvesting options.</td></tr>
<tr><td>Tillage type

Name in file:
<code>PrimaryTillType</code>
Name in code:
<code>PrimaryTillageType</code></td><td>Tillage type is a categorised option listing available tillage practices which when selected will define residue reduction and roughness ratio.
Range: Different options and their effect on residue and roughness are shown in the table below.
<table>
<tr><th>Tillage Implement</th><th>Residue reduction (%)</th><th>Roughness ratio</th></tr>
<tr><td>Stubble burnt</td><td>95</td><td>0.0</td></tr>
<tr><td>Disc Plough</td><td>60</td><td>1.0</td></tr>
<tr><td>Planter</td><td>50</td><td>0.0</td></tr>
<tr><td>Scarifier</td><td>40</td><td>0.7</td></tr>
<tr><td>Chisel Plough</td><td>35</td><td>0.6</td></tr>
<tr><td>Blade plough</td><td>20</td><td>0.3</td></tr>
<tr><td>Sweep plough</td><td>18</td><td>0.3</td></tr>
<tr><td>Rod Weeder</td><td>10</td><td>0.2</td></tr>
<tr><td>Herbicide</td><td>0</td><td>0.0</td></tr>
</table>
Suggested Values: You pick!</td></tr>
<tr><td>Start tillage window
<i>Visible when “Tillage Format” is set to “Automatic”.</i>
Name in file:
<code>StartTillWindow (day, month)</code>
Name in code:
<code>TillageWindowStartDay, TillageWindowStartMonth</code></td><td>Day and Month defining the start of the window when “automatic” tillage may occur.
Range: 1 Jan to 31 Dec
Suggested Values: no suggestions</td></tr>
<tr><td>End tillage window
<i>Visible when “Tillage Format” is set to “Automatic”.</i>
Name in file:
<code>EndTillWindow (day, month)</code>
Name in code:
<code>TillageWindowEndDay, TillageWindowEndMonth</code></td><td>Day and Month defining the end of the window when “automatic” tillage may occur.
Range: 1 Jan to 31 Dec
Suggested Values: no suggestions</td></tr>
</table>

Accumulated rainfall for tillage (mm)
Visible when “Tillage Format” is set to “Automatic”.
Name in file:
`RainForPrimaryTill`
Name in code:
`RainfallForPrimaryTillage`
	Minimum rainfall (mm) required before tillage can occur. Is accompanied by “Number of days to total rain”.
	Range: 0 to 1000
	Suggested Values: Set to 0 to ignore rainfall effects. Otherwise set to sensible value - i.e. 25mm

Number of days to total rain (days)
Visible when “Tillage Format” is set to “Automatic”.
Name in file:
`NoDaysToTotalRain`
Name in code:
`DaysToSumTillageRain`
	Number of days that rainfall will be summated over to see if tillage can occur. Is accompanied by “Accumulated rainfall for tillage”.
	Range: 1 to 10000
	Suggested Values: Usually only a few days to a week.

Minimum number of days between tillage
Visible when “Tillage Format” is set to “Automatic”.
Name in file:
`MinDaysBetweenTills`
Name in code:
`MinDaysBetweenTillage`
	Minimum days between till events.
	Range: 1 to 10000
	Suggested Values: i.e. 30 days.

Tillage date 1, 2, 3, 4 *Visible when “Tillage Format” is set to “Fixed dates (annual)”.* **Name in file:** `TillageDate1,TillageDate2 etc` **Name in code:** `TillageDate1,TillageDate2 etc`	Specific dates for tillage (day and month) for the “fixed dates” option. 4 “slots” are available, but they can be left blank if you don’t want to use all 4 tillage slots. **Range:** Jan 1 to Dec 31 **Suggested Values:** no suggestions
Tillage Dates *Visible when “Tillage Format” is set to “Sequence”.* **Name in file:** `TillageDates` **Name in code:** `TillageDates`	Allows you to define a sequence of tillage events in “dd/mm/yyyy” format separated by a comma. **Range:** Jan 1 to Dec 31 **Suggested Values:** You will need to define all tillage dates from start of the simulation (i.e. 1950) through until today.

Appendix 5 – Irrigation input parameters

Irrigation Scheduling **Name in file:** `IrrigationFormat` **Name in code:** `IrrigationFormat`	Scheduling options. Five options are available based on fixed soil water requirement or percentage PAWC. The last option allows you to define a sequence of dates and amounts. **Range:** “Fixed Soil-Water Req. (only while crop is growing”, “Fixed Soil-Water Req. (within predefined irrigation window)”, “50% PAWC (only while crop is growing)”, “50% PAWC (within predefined irrigation window)”,” Predefined Dates and Amount”. **Suggested Values:** no suggestion.

Start of irrigation window
Visible when “Irrigation Scheduling” is set to “Fixed Soil-Water Req. (with predefined irrigation window)” or “50% PAWC (within predefined irrigation window)”.
Name in file:
`StartIrrigationWindow`
Name in code:
`IrrigationWindowStartDay,`
`IrrigationWindowStartMonth`
	Start of the irrigation window (day and month) for which to consider irrigating.
	Range: 1 Jan to 31 Dec
	Suggested Values: no suggestions.

End of irrigation window
Visible when “Irrigation Scheduling” is set to “Fixed Soil-Water Req. (with predefined irrigation window)” or “50% PAWC (within predefined irrigation window)”.
Name in file:
`EndIrrigationWindow`
Name in code:
`IrrigationWindowEndDay,`
`IrrigationWindowEndMonth`
	End of the irrigation window (day and month) for which to consider irrigating.
	Range: 1 Jan to 31 Dec
	Suggested Values: no suggestions.

Irrigation Dates
Visible when “Irrigation Scheduling” is set to “Predefined Dates and Amounts”
Name in file:
`IrrigationDates`
Name in code:
`IrrigationDateList,`
`IrrigationValueList`
	Sequence of dates (dd/mm/yyyy) and amounts (millimetres) separated by commas.
	Range: -
	Suggested Values: no suggestions

SWD to trigger Irrigation (mm)
Visible when “Irrigation Scheduling” is **NOT** set to “Predefined Dates and Amounts”
Name in file:
`SWDToIrrigate`
Name in code:
`IrrigationSWD`
	Soil water deficit amount (in mm) which must occur before irrigation can be considered.
	Range: 10-400mm
	Suggested Values: usually about 20-50% of the PAWC

Target Amount Visible when "Irrigation Scheduling" is **NOT** set to "Predefined Dates and Amounts" **Name in file:** `TargetAmountOptions` **Name in code:** `TargetAmountOptions`	Target amount shows preconfigured amounts of irrigation water that we will attempt to apply to the soil. Note that water could be limiting in the storage, and runoff and evaporation losses could occur. **Range:** "Field Capacity(DUL)", "Saturation", "Fixed Amount", "DUL+25% Deficit", "DUL+50% Deficit", "DUL + 70% Deficit", "DUL-10% PAWC". **Suggested Values:** no-suggestions

Use Ponding
Name in file:
`Ponding`
Name in code:
`UsePonding`
	"Use ponding" is a switch that when selected sets soil evaporation to potential soil evaporation when ponding conditions exists.
	Range: YES or NO
	Suggested Values: Only use this in crops which are ponded – such as rice paddies.

Use Ring-Tank **Name in file:** `UseRingTank` **Name in code:** `UseRingTank`	Activates the ring-tank submodel. **Range:** YES or NO **Suggested Values:** Select yes if you want to limit irrigation water supply to that contained in a storage.
Ring-Tank Depth (m) Visible when "Use Ring-Tank" is set to "YES". **Name in file:** `RingTankDepth` **Name in code:** `RingTankDepth`	Depth of ring tank **Range:** 0 to 100m **Suggested Values:** based on geometry of storage
Ring-Tank Area (m^2) Visible when "Use Ring-Tank" is set to "YES". **Name in file:** `RingTankArea` **Name in code:** `RingTankArea`	Area of ring tank **Range:** positive number **Suggested Values:** based on geometry of storage
Catchment Area (m^2) Visible when "Use Ring-Tank" is set to "YES". **Name in file:** `CatchmentArea` **Name in code:** `CatchmentArea`	Catchment area is the area of land (m^2) from which when rainfall falls, will cause runoff directly into the ring-tank. **Range:** positive number **Suggested Values:** based on farm conditions
Irrigated Area (m^2) Visible when "Use Ring-Tank" is set to "YES". **Name in file:** `IrrigatedArea` **Name in code:** `IrrigatedArea`	Cropping area that is irrigated **Range:** positive number **Suggested Values:** based on farm conditions
Runoff Capture Rate (mm/day) Visible when "Use Ring-Tank" is set to "YES". **Name in file:** `RunoffCaptureRate` **Name in code:** `RunoffCaptureRate`	Determines how much runoff water can be captured/pumped into the pond. **Range:** positive number **Suggested Values:** based on pump capacity
Ring-Tank Seepage (mm/day) Visible when "Use Ring-Tank" is set to "YES".	Seepage is the amount of water lost per day due to a leaky ring-tank! **Range:** positive number

Name in file:
`RingTankSeepage`
Name in code:
`RingTankSeepageRate`
	Suggested Values: i.e. 5 mm

Evaporation Coefficient (fraction)
Visible when “Use Ring-Tank” is set to “YES”.
Name in file:
`RingTankEvapCoeficient`
Name in code:
`RingTankEvapCoefficient`
	Used to multiply by pan evaporation to work out how much water evaporates from the surface of the pond.
	Range: 0 to 10
	Suggested Values: i.e. 0.1

Delivery Efficiency (%)
Visible when “Use Ring-Tank” is set to “YES”.
Name in file:
`IrrigationDeliveryEfficiency`
Name in code:
`DeliveryEfficiency`
	Accounts for what proportion of the water that leaves the pond for irrigation is actually applied to the field.
	Range: 0-100%
	Suggested Values: would typically be 80-95%

Reset Ring Tank Visible when “Use Ring-Tank” is set to “YES”. **Name in file:** `ResetRingTank` **Name in code:** `ResetRingTank`	Reset Ring Tank is a switch that can be used to reset the storage capacity of the ring tank on a defined date to a defined value. Note that this will upset the volume balance of the system but is useful in studies that look at non-continuous simulations (i.e. generating plumes or horse-tail graphs). **Range:** YES or NO **Suggested Values:** Not recommended – only for certain types of studies.

Ring Tank Reset Date
Visible when “Use Ring-Tank” is set to “YES” and “Reset Ring Tank” is set to “YES”.
Name in file:
`RingTankResetDate`
Name in code:
`RingTankResetDay,`
`RingTankResetMonth`
	Date at which storage reset will occur (Day and Month)
	Range: 1 Jan to 31 Dec
	Suggested Values: none

Capacity at Reset (%) Visible when “Use Ring-Tank” is set to “YES” and “Reset Ring Tank” is set to “YES”. **Name in file:** `CapactityAtReset` **Name in code:** `CapactityAtReset`	Storage reset value (% of capacity) **Range:** 0 to 100% **Suggested Values:** none

Appendix 6 – Pesticide input parameters

A6.1 Parameter descriptions

Application Timing **Name in file:** `PestApplicationTiming` **Name in code:** `PestApplicationTiming`	Options to define when a pesticide is applied **Range:** "Fixed date", "Predefined dates and rates", "Growing degree days", "Days after sowing", "Days since fallow" **Suggested Values:** none provided

Application Date
Visible when "Application Timing" is set to "Fixed date".
Name in file:
`ApplicationDate (Day,Month)`
Name in code:
`PesticideApplicationDay,`
`PesticideApplicationMonth`
	Fixed application date for single pesticide application
	Range: 1 Jan to 31 Dec
	Suggested Values: none provided

Product rate (l/ha) *Visible when "Application Timing" is NOT set to "Predefined dates and rates".* **Name in file:** `ProductRate` **Name in code:** `ProductRate`	Amount of pesticide applied for first application of the season **Range:** 0 to 1000 **Suggested Values:** none provided
Subsequent Product rate (l/ha) *Visible when "Application Timing" is NOT set to "Predefined dates and rates".* **Name in file:** `SubsequentProductRate` **Name in code:** `SubsequentProductRate`	Amount of pesticide applied for subsequent applications of the season **Range:** 0 to 1000 **Suggested Values:** none provided

Dates & Rates(l/ha)
Visible when "Application Timing" is set to "Predefined dates and rates".
Name in file:
`PesticideDatesAndRates`
Name in code:
`PestApplicationDateList`
	Sequence of comma separated dates (dd/mm/yyy) and pesticide application rates.
	Range: Dates must be in simulation range.
	Suggested Values: none provided

Apply to Vegetation "X"
Visible when "Application Timing" is set to "Growing Degree Days" or "Days after Sowing".
Name in file:
`tbPestVegIndex1,tbPestVegIndex2,etc`
Name in code:
`PestApplicationDateList`
	Defines what crops the scheduling rules relate to.
	Range: YES or NO
	Suggested Values: none provided

Trigger first spray (oC)
Visible when "Application Timing" is set to "Growing Degree Days".
Name in file:
`TriggerGGDFirst`
Name in code:
`PestTriggerGGDFirst`
	Growing degree days for first spray
	Range: 0 to 10000
	Suggested Values: none provided

Trigger subsequent sprays (oC)
Visible when "Application Timing" is set to "Growing Degree Days".
Name in file:
`TriggerGGDSubsequent`
Name in code:
`PestTriggerGGDSubsequent`
	Growing degree days for subsequent sprays
	Range: 0 to 10000
	Suggested Values: none provided

Trigger first spray (days)
Visible when "Application Timing" is set to "Days after sowing" OR "Days since fallow".
Name in file:
`TriggerDaysFirst`
Name in code:
`PestTriggerDaysFirst`
	Days after sowing (or fallow) for first spray
	Range: 0 to 10000
	Suggested Values: none provided

Trigger subsequent sprays (days)
Visible when "Application Timing" is set to "Days after sowing" OR "Days since fallow".
Name in file:
`TriggerDaysSubsequent`
Name in code:
`PestTriggerDaysSubsequent`
	Days after sowing (or fallow) for subsequent sprays
	Range: 0 to 10000
	Suggested Values: none provided

Application Position
Name in file:
`PestApplicationPosition`
Name in code:
`PesticideApplicationPosition`
	Describes where the pesticide is applied relative to the crop. It is used to determine the fraction of the applied pesticide that is assumed to have been intercepted by the vegetation and/or stubble rather than entering the soil.
	Range: "Above Canopy", "Below Canopy/Above Mulch", "Direct to Soil"

Half-life (Veg) (days) *Visible when "Application Position" is set to "Above Canopy".* **Name in file:** `HalfLifeVeg` **Name in code:** `HalfLifeVeg`	The time required (days) for a pesticide to undergo dissipation or degradation to half of the initial concentration on the vegetation. **Range:** 1 to 5000 **Suggested Values:** Depends on pesticide properties and climate. In absence of alternative data, use soil half-life.

Reference Temperature for Half-life (Veg) (oC)
Visible when "Application Position" is set to "Above Canopy".
Name in file:
`RefTempHalfLifeVeg`
Name in code:
`HalfLifeRefTempVeg`
	The mean air temperature at which the Half-life (Veg) was determined (oC).
	Range: 0 to 50
	Suggested Values: Refer to source of half-life data for reference temperatures.

Half-life (Stubble) (days) *Visible when "Application Position" is set to "Above Canopy" or "Below canopy/Above mulch".* **Name in file:** `HalfLifeStubble` **Name in code:** `HalfLifeStubble`	The time required (days) for a pesticide to undergo dissipation or degradation to half of the initial concentration in the stubble. **Range:** 1 to 5000 **Suggested Values:** The time required (days) for a pesticide to undergo dissipation or degradation to half of the initial concentration in the stubble.

Reference Temperature for Half-life (Stubble) (oC)
Visible when "Application Position" is set to "Above Canopy" or "Below canopy/Above mulch".
Name in file:
`RefTempHalfLifeStubble`
Name in code:
`HalfLifeRefTempStubble`
	The mean air temperature at which the Half-life (Stubble) was determined (oC).
	Range: 0 to 50
	Suggested Values: Refer to source of half-life data for reference temperatures.

Half-life (Soil) (days)
Name in file:
`HalfLife`
Name in code:
`HalfLifeSoil`
	The time required (days) for a pesticide to under go dissipation or degradation to half of the initial concentration in the soil.
	Range: 1 to 5000
	Suggested Values: Depends on pesticide properties, soil properties and climate. Estimates for temperate environments are available through the Pesticides Properties Database, Footprint.

Reference Temperature for Half-life (Soil) (oC)
Name in file:
`RefTempHalfLifeSoil`
Name in code:
`HalfLifeRefTempSoil`
	The mean air temperature at which the Half-life (Soil) was determined (oC).
	Range: 0 to 50
	Suggested Values: Refer to source of half-life data for reference temperatures.

Degradation Activation Energy (J/mol)
Name in file:
`DegradationActivationEnergy`
Name in code:
`DegredationActivationEnergy`
	The energetic threshold for thermal decomposition reactions (J/mol).
	Range: 5000 to 100000
	Suggested Values: The default value of 65400 J/mol has been proposed by the European Food Safety Authority (EFSA, 2007. Scientific opinion of the panel on plant protection products and their residues on a request from EFSA related to the default Q10 value used to describe the temperature effect on transformation rates of pesticides in soil. The EFSA Journal, 622, 1-3.). EFSA (2007) concluded that Some pesticide specific values are available from the literature.

Band Spraying (%) **Name in file:** `BandSpraying` **Name in code:** `BandSpraying`	The percent area of a paddock to which a pesticide is applied. **Range:** 0 to 100 **Suggested Values:** Default to 100%, otherwise use the % of a paddock sprayed.

Concentration of active ingredient (g/L)
Name in file:
`ConcActiveIngred`
Name in code:
`IngredConcentration`
	The concentration of the pesticide active ingredient (e.g. glyphosate) in the applied product (e.g. Roundup) (g/L). This value is multiplied by the application rate (L/ha) to calculate the amount of active ingredient applied (kg/ha).
	Range: 0 to 10000
	Suggested Values: Depends on pesticide product. Refer to product labels.

Application efficiency (%)
Name in file:
`PestEfficiency`
Name in code:
`PesticideEfficiency`
	The percent of total applied pesticide (concentration of active ingredient x application rate) that is retained in the paddock (on the vegetation, stubble or soil) immediately following application. This percent may be less than 100 if there is significant spray drift or other losses between the point of application and the vegetation, stubble and soil.
	Range: 0 to 100%
	Suggested Values: Default to 100% unless there is evidence of pesticide loss between point of application and delivery to the veg/stubble/soil.

Mixing layer thickness (mm) **Name in file:** `MixLayerThickness` **Name in code:** `MixLayerThickness`	Depth of the surface soil layer into which an applied pesticide is mixed (mm). This depth is used to calculate a pesticide concentration in the soil following application. **Range:** 1 to 100mm **Suggested Values:** Default to 25 unless alternative data is available.
Sorption Coefficient **Name in file:** `SorptionCoefficient` **Name in code:** `SorptionCoefficient`	The sorption coefficient is the ratio of the amount of pesticide bound to soil/sediment versus the amount in the water phase (Kd). Kd values can be derived empirically or estimated from published organic carbon sorption coefficients (Koc) where Kd=Koc x fraction of organic carbon. **Range:** 0.001 to 1000000 **Suggested Values:** Depends on pesticide and soil properties. Literature should be consulted.

Extraction Coefficient
Name in file:
`ExtractCoefficient`
Name in code:
`ExtractionCoefficient`
	The fraction of pesticide present in soil that will be extracted into runoff. This includes pesticides present in runoff in both the sorbed and dissolved phase. The value of 0.02 has been derived empirically (Silburn, 2003). Characterising pesticide runoff from soil on cotton farms using a rainfall simulator. PhD Thesis, University of Sydney.) and was found to be relevant to data from a range of published studies.
	Range: 0.001 to 100
	Suggested Values: Default to 0.02 unless alternative empirical evidence is available.

Cover washoff fraction **Name in file:** `CoverWashoffFraction` **Name in code:** `CoverWashoffFraction`	The fraction of a pesticide that will move off the surface of the vegetation or stubble and into the soil following a rainfall event of greater than 5mm. **Range:** 0 to 1 **Suggested Values:** Depends on pesticide properties. Estimates are available for some pesticides in the SWAT pesticides database (Neitsch, SL, Arnold, JG, Kiniry, JR, Srinivasan, R and Williams, JR, 2004. Soil and water assessment tool: input/output file documentation Version 2005. Grassland, Soil and Water Research Laboratory, Texas.)

Critical Pest Concentration (ug/l) **Name in file:** `CritPestConc` **Name in code:** `CritPestConc`	Concentration of a pesticide that should not be exceeded in runoff (ug/L). **Range:** 0 to 1 ug/L **Suggested Values:** Refer to locally relevant water quality guidelines or toxicity data.

A6.2 Sample Pesticide Data Files

A6.2.1 24-D - wheatC

Name	CurrentValue
Application Timing	Days after sowing
Apply to Vegetation 1	No
Apply to Vegetation 2	Yes
Apply to Vegetation 3	No
Apply to Vegetation 4	No
Apply to Vegetation 5	No
Apply to Vegetation 6	No
Apply to Vegetation 7	No
Apply to Vegetation 8	No
Apply to Vegetation 9	No
Apply to Vegetation 10	No
Trigger first spray	60
Trigger subsequent sprays	1
Product rate	1.7 l/ha
Subsequent Product rate	0 l/ha
Application Position	Above Canopy
Half-life (Veg)	5 days
Reference Temperature for Half-life (Veg)	25 oC
Half-life (Stubble)	5 days
Reference Temperature for Half-life (Stubble)	25 oC
Half-life (Soil)	10 days
Reference Temperature for Half-life (Soil)	25 oC
Degradation Activation Energy	65400 J/mol
Band Spraying (%)	100
Concentration of active ingredient	500 g/L
Application efficiency	100 %
Mixing layer thickness	25
Sorption Coefficient	56
Extraction Coefficient	0.02
Cover washoff fraction	0.45
Critical Pest Concentration	1 ug/l

A6.2.2 Ametryn - sorghumB

Name	CurrentValue
Application Timing	Days after sowing
Apply to Vegetation 1	Yes
Apply to Vegetation 2	No
Apply to Vegetation 3	No
Apply to Vegetation 4	No
Apply to Vegetation 5	No
Apply to Vegetation 6	No
Apply to Vegetation 7	No
Apply to Vegetation 8	No
Apply to Vegetation 9	No
Apply to Vegetation 10	No
Trigger first spray	1
Trigger subsequent sprays	1
Product rate	1.5 l/ha
Subsequent Product rate	0 l/ha
Application Position	Above Canopy
Half-life (Veg)	10.5 days
Reference Temperature for Half-life (Veg)	25 oC
Half-life (Stubble)	10.5 days
Reference Temperature for Half-life (Stubble)	25 oC
Half-life (Soil)	21 days
Reference Temperature for Half-life (Soil)	25 oC
Degradation Activation Energy	49400 J/mol
Band Spraying (%)	100
Concentration of active ingredient	960 g/L
Application efficiency	100 %
Mixing layer thickness	25
Sorption Coefficient	200
Extraction Coefficient	0.02
Cover washoff fraction	0.6
Critical Pest Concentration	0.02 ug/l

A6.2.3 Atrazine - CaneC

Based on Atrazine - sorghumC
from
DERM 2012 Shaw, Robinson Silburn notes for Paddock to Reef water quality modelling activity
DMF 120921

Name	CurrentValue
Application Timing	Fixed Date
Application Date	10 Sep
Product rate	0.5 l/ha
Subsequent Product rate	0 l/ha
Application Position	Below canopy/Above mulch
Half-life (Stubble)	14.5 days
Reference Temperature for Half-life (Stubble)	25 oC
Half-life (Soil)	29 days
Reference Temperature for Half-life (Soil)	25 oC
Degradation Activation Energy	54900 J/mol
Band Spraying (%)	100
Concentration of active ingredient	900 g/L
Application efficiency	100 %
Mixing layer thickness	25
Sorption Coefficient	1
Extraction Coefficient	0.02
Cover washoff fraction	0.45
Critical Pest Concentration	1 ug/l

Appendix 7- Phosphorus input parameters

Dissolved P Methodology **Name in file:** `DissolvedPOption` **Name in code:** `DissolvedPOption`	Two options. VIC DPI Method: p_max_sorption = 1447 * (1-exp(-0.001 * PBI)), QLD REEF Method: p_max_sorption=5.84*PBI-0.0096*PBI^2 (min of 50). Phos_Conc_Dissolve_mg_per_L is also calculated slightly differently. **Range:** "VIC PEI", "QLD Reef"
Total P Concentration (mg/kg) **Name in file:** `TotalPConc` **Name in code:** `TotalPConc`	The total P content of the soil (extracted with hot acid) **Range:** 0 to 2500 mg/kg **Suggested Values:** Sandy soils = 20 to 200, Loamy soils = 50 to 500, Clay soils = 100 to 1000
ColwellP (mg/kg) **Name in file:** `ColwellP` **Name in code:** `ColwellP`	The amount of easily-extracted P in the topsoil (0-10 cm, extracted with bicarbonate). **Range:** 0 to 1000 **Suggested Values:** Infertile sand = 2 to 5, Fertile sand = 5 to 15, Infertile loam = 5 to 10, Fertile loam = 10 to 20, Infertile clay = 5 to 10, Fertile clay = 10 to 50, Fertile alluvial clays = 20 to 100, Ferrosols = 20 to 100

Phosphorus Buffing Index
 	
Name in file:
`XXXXX`
Name in code:
`PBI`
	The degree to which soils bind P (related to the %clay, clay weathering and Fe content)
	Range: 1 to 1000
	Suggested Values: Extremely low (sand) = 10, Very low (loamy sand) = 40, Low (loam) = 100, Medium (clay) = 200, High (weathered neutral clay) = 500, Very High (weathered acid clays - Ferrosols) = 1000

Total P Enrichment Options
 	
Name in file:
`DissolvedPOption`
Name in code:
`PEnrichmentOption`
	The choices are between a constant value (good where there is no detailed information) and a simple function based on Clay percentage (good where variations occur in clay%),
	Range: "Constant Ratio", "Empirical Clay Fn."

P Enrichment Ratio
Visible when "Total P Enrichments Options" is set to "Constant Ratio".
 	
Name in file:
`EnrichmentRatio`
Name in code:
`pEnrichmentRatio`
	The ratio of total P in sediment to the topsoil (0-10 cm).
	Range: 0.5 to 10
	Suggested Values: Sandy, untilled soil = 10, Sandy, tilled soil = 4, Loamy, untilled soil = 7, Loamy, tilled soil = 5, Clay soil = 1.5

Percentage Clay (%) *Visible when "Total P Enrichments Options" is set to "Empirical Clay Fn".* **Name in file:** `ClayPercentage` **Name in code:** `ClayPercentage`	The percent clay in the soil (clay particles are <2um in size). **Range:** 0 to 100% **Suggested Values:** Sand = 5, Sandy loam = 10, Loam = 20, Clay loam = 30, Loamy clay = 40, Clay = 50, Heavy clay = 60

Appendix 8 – Nitrate input parameters

Dissolved N in Runoff Parameters	

Dissolved N in Runoff Options
Name in file:
`DissolvedNinRunoffOptions`
Name in code:
`NDepthTopLayer1`
	Calculation options for dissolved N in runoff. The two main options require you to provide a Nitrate profile in the soil. The two empirical options required fertiliser application rates and dates, and don't consider N profile in the soil.
	Range: "None", "Imported Time Series", "User-defined profile", "Rattray Empirical Model", "Fraser Empirical Model"
	Suggested Values: Designed for import time-series- other options are add-ons!

Depth of top layer (for N movement)
Visible when "Dissolved N in Runoff Options" is set to "Imported time-series" OR "User-defined profile".
Name in file:
`NDepthTopLayer1`
Name in code:
`XXXX`
	Active depth of top layer – not necessarily the same as layer depth.
	Range: less than or equal to layer 1 depth.
	Suggested Values: 20mm

k (soil water/runoff mixing factor) *Visible when "Dissolved N in Runoff Options" is set to "Imported time-series" OR "User-defined profile" OR "Fraser Empirical model".* **Name in file:** `Nk` **Name in code:** `Nk`	Parameter that regulates mixing of soil and runoff water with a suggested value is 0.5 **Range:** -1000 to 10000 **Suggested Values:** 0.5
cv (soil water/runoff curvature factor) *Visible when "Dissolved N in Runoff Options" is set to "Imported time-series" OR "User-defined profile".* **Name in file:** `Ncv` **Name in code:** `Ncv`	Describes the curvature of change in soil and water runoff at increasing runoff values (initial guess is 0.2) **Range:** -1000 to 10000 **Suggested Values:** 0.2
Alpha (dissolved N calibration factor) *Visible when "Dissolved N in Runoff Options" is set to "Imported time-series" OR "User-defined profile".* **Name in file:** `NAlpha` **Name in code:** `NAlpha`	Conversion factor that can be used also for calibration**.** **Range:** -1000 to 10000 **Suggested Values:** 1
Power fit Alpha value *Visible when "Dissolved N in Runoff Options" is set to "Rattray Empirical Model".* **Name in file:** `N_DanRat_Alpha` **Name in code:** `N_DanRat_Alpha`	Alpha parameter of power-curve relationship of Rattray Model**.** **Range:** -1000 to 10000 **Suggested Values:** not-available

Power fit Beta value *Visible when “Dissolved N in Runoff Options” is set to “Rattray Empirical Model”.* **Name in file:** `N_DanRat_Beta` **Name in code:** `N_DanRat_Beta`	Beta parameter of power-curve relationship of Rattray Model**.** **Range:** -1000 to 10000 **Suggested Values:** not-available
Max runoff conc *Visible when “Dissolved N in Runoff Options” is set to “Rattray Empirical Model”.* **Name in file:** `N_DanRat_MaxRunOffConc` **Name in code:** `N_DanRat_MaxRunOffConc`	Maximum N runoff concentration used in Rattray Model. Limits the result from power curve relationship. **Range:** positive value **Suggested Values:** not-available
Min runoff conc *Visible when “Dissolved N in Runoff Options” is set to “Rattray Empirical Model”.* **Name in file:** `N_DanRat_MinRunOffConc` **Name in code:** `N_DanRat_MinRunOffConc`	Minimum N runoff concentration used in Rattray Model. Limits the result from power curve relationship. **Range:** positive value **Suggested Values:** not-available
Daily loss proportion *Visible when “Dissolved N in Runoff Options” is set to “Fraser Empirical Model”.* **Name in file:** `N_GraFraz_DL` **Name in code:** `N_GraFraz_DL`	Daily loss proportion of the Fraser Model. **Range:** positive value **Suggested Values:** not-available
Rainfall loss-DIN loss per mm/rain irrig *Visible when “Dissolved N in Runoff Options” is set to “Fraser Empirical Model”.* **Name in file:** `N_GraFraz_RL` **Name in code:** `N_GraFraz_RL`	Rainfall loss component of the Fraser Model. **Range:** positive value **Suggested Values:** not-available

Lower limit DIN conc (approach rainfall)
Visible when “Dissolved N in Runoff Options” is set to “Fraser Empirical Model”.
Name in file:
`N_GraFraz_LowLimitDINConc`
Name in code:
`XXXX`
	Lower limit DIN concentration (approaching rainfall) component of the Fraser Model.
	Range: positive value
	Suggested Values: not-available

Fertiliser Application Sequence
Visible when “Dissolved N in Runoff Options” is set to “Rattray Empirical Model” OR “Fraser Empirical Model”.
Name in file:
`FertilizerInputDateSequences`
Name in code:
`XXXX`
	List of comma-separated dates (dd/mm/yyyy format) and application rates for the Rattray and Fraser Models
	Range: positive value
	Suggested Values: not-available

Source Data File
Visible when “Dissolved N in Runoff Options” is set to “Imported time-series”.
Name in file:
`NitrateSourceData`
Name in code:
`XXXX`
	Links to an existing time-series file containing “N03 N store in the top layer” in ***HowLeaky***, or you can import a new time-series using the dropdown menu. Was designed to import a ***DairyMod*** file.
	Range: Date range should be between start date and end date of simulation.
	Suggested Values: -

NO3 N store in top layer (kg/ha)
Visible when “Dissolved N in Runoff Options” is set to “Imported time-series”.
Name in file:
`SoilNitrateTimeseries`
Name in code:
`XXXX`
	Select a time-series from your source-data file.
	Range: Will list all time-series in the file.
	Suggested Values: -

NO3 N store in top layer (kg/ha)
Visible when “Dissolved N in Runoff Options” is set to “User defined profile”.
Name in file:
`SoilNitrateLevels (Data x,y,z,a)`
Name in code:
`XXXX`
	Total N03 N store in top layer put in as a profile (time-series) of Julian days and amounts.
	Range: -
	Suggested Values: really need 1 daily value per month (12 months) – daily values will be interpolated.

NO3 N Store scaling factor
Visible when “Dissolved N in Runoff Options” is set to “Imported time-series” OR “User defined profile”.
Name in file:
`SoilNitrateLoadWeighting1`
Name in code:
`XXXX`
	Used to calibrate or adjust all values in the imported time-series or profile.
	Range: 0 to big number – usually around 1
	Suggested Values: 1

Dissolved N in Leaching Options
Name in file:
`DissolvedNinLeachingOptions`
Name in code:
`XXXX`
	Options to for importing N data in bottom layer.
	Range: “None”, “Imported time-series”, “user-defined profile”
	Suggested Values: no suggestions

Depth of bottom layer (for N movement)
Visible when “Dissolved N in Leaching Options” is NOT set to “none”.
Name in file:
`DepthBottomLayer`
Name in code:
`NDepthBottomLayer`
	Depth of bottom layer
	Range: See soil properties
	Suggested Values: See soil properties

Nitrate leaching efficiency *Visible when “Dissolved N in Leaching Options” is NOT set to “none”.* **Name in file:** `NitrateLeachingEfficiency` **Name in code:** `NitrateLeachingEfficiency`	Efficiency parameter used to extract a proportion of N concentration in bottom layer for drainage. **Range:** 0-1 **Suggested Values:** i.e. 0.5

Source data file
Visible when "Dissolved N in Leaching Options" is set to "Imported time-series".
Name in file:
`NitrateSourceData`
Name in code:
`XXXX`
	Links to an existing time-series file containing "NO3 store in bottom layer" in ***HowLeaky***, or you can import a new time-series using the dropdown menu. Was designed to import a ***DairyMod*** output file.
	Range: Date range should be between start date and end date of simulation.
	Suggested Values: -

NO3 N store in bottom layer (kg/ha)
Visible when "Dissolved N in Leaching Options" is set to "Imported time-series".
Name in file:
`SoilNitrateTimeseries`
Name in code:
`XXXX`
	Select a time-series from your source-data file.
	Range: Will list all time-series in the file.
	Suggested Values: -

NO3 N store scaling factor
Visible when "Dissolved N in Leaching Options" is NOT set to "none".
Name in file:
`SoilNitrateLoadWeighting2`
Name in code:
`XXXX`
	Used to calibrate or adjust all values in the imported time-series or profile.
	Range: 0 to big number – usually around 1
	Suggested Values: 1

NO3 N store in bottom layer (kg/ha)
Visible when "Dissolved N in Leaching Options" is set to "User-defined profile".
Name in file:
`SoilNitrateLevels`
Name in code:
`XXXX`
	Total N03 N store in bottom layer put in as a profile (time-series) of Julian days and amounts.
	Range: -
	Suggested Values: really need 1 daily value per month (12 months) – daily values will be interpolated.

Particulate N in runoff options
Name in file:
`ParticulateNinRunoffOptions`
Name in code:
`XXXX`
	Options for importing N data (time-series or profile) in top layer.
	Range: "None", "Imported time-series", "user-defined profile"
	Suggested Values: no suggestions

Depth of top layer (for N movement) *Visible when "Particulate N in Runoff Options" is NOT set to "none".* **Name in file:** `NDepthTopLayer2` **Name in code:** `NDepthTopLayer2`	Active depth of top layer – not necessarily the same as layer depth. **Range:** less than or equal to layer 1 depth. **Suggested Values:** 20mm
N Enrichment ratio *Visible when "Particulate N in Runoff Options" is NOT set to "none".* **Name in file:** `NEnrichmentRatio` **Name in code:** `NEnrichmentRatio`	Used to estimate N loss associated with erosion. **Range:** positive value **Suggested Values:** not available

Alpha (Dissolved N calibration factor) *Visible when "Particulate N in Runoff Options" is NOT set to "none".* **Name in file:** `NAlpha` **Name in code:** `NAlpha`	Conversion factor to adjust units **Range:** not available **Suggested Values:** not available
Beta (Particulate N calibration factor) *Visible when "Particulate N in Runoff Options" is NOT set to "none".* **Name in file:** `NBeta` **Name in code:** `NBeta`	Conversion factor to adjust units **Range:** not available **Suggested Values:** not available

Source Data
Visible when "Particulate N in Runoff Options" is set to "Imported time-series".
Name in file:
`NitrateSourceData`
Name in code:
`–`
	Links to an existing time-series file containing 3 time-series including "Inorganic Nitrate N ", "Inorganic Ammonium N" and "Organic N in the top layer"; or you can import a new time-series using the dropdown menu. Was designed to import a ***DairyMod*** output file.
	Range: Date range should be between start date and end date of simulation.
	Suggested Values: -

Inorganic Nitrate N (top layer) kg/ha
Visible when "Particulate N in Runoff Options" is set to "Imported time-series".
Name in file:
`InorganicNitrateNTimeseries`
Name in code:
`XXXX`
	Select a time-series from your source-data file.
	Range: Will list all time-series in the file.
	Suggested Values: -

Inorganic Ammonium N (top layer) kg/ha
Visible when "Particulate N in Runoff Options" is set to "Imported time-series".
Name in file:
`InorganicAmmoniumNTimeseries`
Name in code:
`XXXX`
	Select a time-series from your source-data file.
	Range: Will list all time-series in the file.
	Suggested Values: -

Organic N (top layer) kg/ha
Visible when "Particulate N in Runoff Options" is set to "Imported time-series".
Name in file:
`OrganicNTimeseries`
Name in code:
`XXXX`
	Select a time-series from your source-data file.
	Range: Will list all time-series in the file.
	Suggested Values: -

Soil Nitrate Loads
Visible when "Particulate N in Runoff Options" is set to "User-defined profile".
Name in file:
`SoilNitrateLevels (Data, x,y,z,a)`
Name in code:
`XXXX`
	Total nitrate loading in top layer put in as a profile (time-series) of Julian days and amounts.
	Range: -
	Suggested Values: really need 1 daily value per month (12 months) – daily values will be interpolated.

Organic N Store scaling factor
Visible when “Particulate N in Runoff Options” is NOT set to “None”.
Name in file:
`SoilNitrateLoadWeighting3`
Name in code:
`XXXX`
	Used to calibrate or adjust all values in the imported time-series or profile.
	Range: 0 to big number – usually around 1
	Suggested Values: 1

Appendix 9 – Solutes input parameters

Initial Solute Concentrations
Name in file:
`InitialStartingConditionsOptions`
Name in code:
`XXXX`
	Option to define how to initialise solute concentration in the soil
	Range: "Constant", "Define Lay1", "Define Lay1-2", "Define Lay1-3", "Define Lay1-4", "Define Lay1-5"

Default Layer Conc. (mg/kg)
Name in file:
`InitialSoilSoluteConcDefault`
Name in code:
`SoluteLayerInitialConcDefault`
	Used to define an initiation concentration in a soil layer that doesn't explicitly have a value defined in the other options.
	Range: positive number
	Suggested Values: -

Layer "X" Conc. (mg/kg)
Visible when "Initial solute conentration" is NOT set to "constant".
Name in file:
`InitialSoilSoluteConc1, 2, 3, etc`
Name in code:
`SoluteLayerInitialConc1`
	Initial solute concentration for a specific layer "X".
	Range: positive number
	Suggested Values: -

Solute Rainfall Concentration (mg/L)
Name in file:
`SoluteRainfallConcentration`
Name in code:
`SoluteRainfallConcentration_mg_per_L`
	Solute concentration in input rainfall.
	Range: positive number
	Suggested Values: -

Solute Irrigation Concentration (mg/L)
Name in file:
`SoluteIrrigaitonConcentration`
Name in code:
`SoluteIrrigationConcentration_mg_per_L`
	Solute concentration in input irrigation water.
	Range: positive number
	Suggested Values: -

Solute Mixing Coefficient **Name in file:** `SoluteMixingCoefficient` **Name in code:** `SoluteMixingCoefficient`	Mixing coefficient used to calculate loadings. **Range:** 0 to 1 **Suggested Values:** -

Appendix 10 – Model options input parameters

Reset residue mass at defined date
 	
Name in file:
`ResetResidueMass`
Name in code:
`ResetResidueAtDate`
	Option to reset residue to a fixed value (kg/ha) at a particular date each year.
	Range: YES or NO
	Suggested Values: -

Date to reset residue
Visible when "Reset residue mass at defined date" is set to YES
Name in file:
`ResetDateForResidue`
Name in code:
`ResetDayForResidue,`
`ResetMonthForResidue`
	Date to reset crop reside
	Range: 1 Jan to 31 Dec
	Suggested Values: not available

Crop residue reset value (kg/ha)
Visible when "Reset residue mass at defined date" is set to YES
Name in file:
`CropResResetValue`
Name in code:
`CropResidueResetValue`
	Amount to reset crop reside to (kg/ha) at the defined date specified above.
	Range: 0 to 100000
	Suggested Values: not available

Reset soil water at defined date
 	
Name in file:
`ResetSoilWater`
Name in code:
`ResetSoilWaterAtDate`
	Option to reset soil water at a defined date. NOTE that this will break the volume balance.
	Range: YES or NO
	Suggested Values: not available

Date to reset soil water
 	
Name in file:
`ResetDateForSoilWater`
Name in code:
`ResetDayForSoilWater,`
`ResetMonthForSoilWater`
	Date to reset soil water.
	Range: 1 Jan to 31 Dec
	Suggested Values: not available

Percentage PAWC at defined date (%)
Visible when "Reset soil water at defined date" is set to YES
Name in file:
`PercentPAWCAtDate`
Name in code:
`SoilWaterResetValueAtDate`
	Percentage of the PAWC that we should reset to.
	Range: 0 to 100%
	Suggested Values: its normally done to set the SW back to full.

Reset soil water at planting **Name in file:** `UpdateSWAfterPlanting` **Name in code:** `UpdateSWAfterPlanting`	Option to reset SW at planting. NOTE that this will break the volume balance. **Range:** YES or NO **Suggested Values:**

Percentage PAWC at planting (%)
Visible when "Reset soil water at planting" is set to YES
 	
Name in file:
`PercentPAWCAtPlanting`
Name in code:
`SoilWaterResetValueAfterPlanting`
	Percentage of the PAWC that we should reset to.
	Range: 0 to 100%
	Suggested Values: its normally done to set the SW back to full.

Calculate Lateral Flow
Name in file:
`CalculateLateralFlow`
Name in code:
`CanCalculateLateralFlow`
	Option to calculate Lateral flow.
	Range: YES or NO
	Suggested Values: NO

Ignore Crop Death
Name in file:
`IgnoreCropDeath`
Name in code:
`IgnoreCropKill`
	Option to ignore crop depth in LAI cropping submodel.
	Range: YES or NO
	Suggested Values: NO

Use PERFECT dry matter fn **Name in file:** `Use_PERFECT_DryMatter` **Name in code:** `Use_PERFECT_DryMatter`	Option to use the original PERFECT dry matter function. **Range:** YES or NO **Suggested Values:** NO
Use PERFECT ground-cover fn **Name in file:** `Use_PERFECT_GCovEqn` **Name in code:** `Use_PERFECT_GCovEqn`	Option to use the original PERFECT ground cover function. **Range:** YES or NO **Suggested Values:** NO

Use PERFECT soil evap fn
Name in file:
`Use_PERFECT_PotSE`
Name in code:
`Use_PERFECT_SoilEvapFn`
	Option to use the original PERFECT soil evaporation functions.
	Range: YES or NO
	Suggested Values: NO

Use PERFECT leaf area fn **Name in file:** `Use_PERFECT_DLAI` **Name in code:** `Use_PERFECT_DLAI`	Option to use the original PERFECT LAI calculations. **Range:** YES or NO **Suggested Values:** NO

Use PERFECT residue fn
Name in file:
`Use_PERFECT_Residue`
Name in code:
`Use_PERFECT_ResidueFunction`
	Option to use the original PERFECT residue functions.
	Range: YES or NO
	Suggested Values: NO

Use PERFECT USLE LS Factor **Name in file:** `Use_PERFECT_USLE_LSFactor` **Name in code:** `Use_PERFECT_USLE_LSFactor`	Option to use the original PERFECT universal soil loss equations slope factor methodology. **Range:** YES or NO **Suggested Values:** NO

Use PERFECT CN fn
Name in file:
`Use_PERFECT_CN`
Name in code:
`Use_PERFECT_CNFunction`
	Option to use the original PERFECT runoff curve number functions.
	Range: YES or NO (DEFAULT IS YES)
	Suggested Values: **RECOMMEND THAT THIS ALWAYS BE SET TO YES – POTENTIAL PROBLEMS WITH NEW FUNCTION**

PAWC factor at start of simulation (fraction) **Name in file:** `InitialPAWC` **Name in code:** `InitialPAWC`	Proportion of PAWC at start of simulation Range: 0-1 Suggested value: 0.5 for half full profile. 1 for full profile. Etc.

Appendix 11 – Outputs

A11.1 Daily timeseries

Inputs
Rainfall (mm)
Maximum temperature (ºC)
Minimum temperatures (ºC)
Pan evaporation (mm)
Solar radiation MJ/m2/day
Water balance
Runoff (mm)
Soil evaporation (mm)
Transpiration (mm)
Evapotranspiration (mm)
Deep drainage (mm)
Overflow (mm)
Potential soil evaporation (mm)
In-crop runoff (mm)
In-crop soil evaporation (mm)
In-crop evapotranspiration (mm)
In-crop deep drainage (mm)
Soil outputs
Hillslope erosion (t/ha)
Off-site sediment delivery (t/ha)
Total available soil water (mm)
Soil water deficit (mm)
Total crop residue (kg/ha)
Total crop residue (%)
Layer Outputs:
Available soil water (mm)
Drainage (mm)
Crop Outputs
Days since planting
Leaf Area Index (if applicable)
Crop cover (%)
Residue cover (%)
Total cover (%)
Crop residue (kg/ha)
Dry matter (kg)
Root depth (mm)

Yield (t/ha)
Potential transpiration
Growth regulator
Ring tank outputs
Evaporation losses (ML)
Seepage losses (ML)
Overtopping losses (ML)
Irrigation losses (ML)
Total losses (ML)
Captured runoff inflow (ML)
Rainfall inflow (ML)
Effective additional inflow (ML)
Total additional inflow (ML)
Total inflow (ML)
Ineffective additional inflow (ML)
Storage volume (ML)
Ring tank storage level (%)
Phosphorous Outputs
Particulate concentration (mg/L)
Dissolved concentration (mg/L)
Bioavailable particulate P concentration (mg/L)
Bioavailable P concentration (mg/L)
Total P concentration (mg/L)
Particulate P export (kg/ha)
Dissolved export (kg/ha)
Bioavailable particulate P export (kg/ha)
Total bioavailable export (kg/ha)
Total phosphorus export (kg/ha)
CKQ (t/ha)
PPHLC (kg/ha)
Pesticides
Applied pest on veg (g/ha
Applied pest on stubble (g/ha)
Applied pest on soil (g/ha)
Pest on veg (g/ha)
Pest on stubble (g/ha)
Pest in soil (g/ha)
Pest soil conc. (mg/kg)
Pest sediment phase conc. (mg/kg)

Pest water phase conc. (ug/L)
Pest runoff conc. (water+sediment) (ug/L)
Sediment delivered (g/L)
Pest lost in runoff water (g/ha)
Pest lost in runoff sediment (g/ha)
Total pest lost in runoff (g/ha)
Pest lost in leaching (g/ha)
Pest losses as percent of last input (%)
Nitrate N
Dissolved N03 N in Runoff (mg/L)
N03 Runoff Load (kg/ha)
Dissolved N03 N in Leaching (mg/L)
N03 N Leaching Load (kg/ha)
Particulate N in Runoff (kg/ha)
PNHLC (kg/ha)
N03 N Store (top layer) (kg/ha)
N03 N Store (bot layer) (kg/ha)
Total N Store (top layer) (kg/ha)
Solutes
Total Soil Solute (Load) (kg/ha)
Total Soil Solute (Concentration) (mg/kg soil)
Total Soil Water Solute (Concentration) (mg/L_soil-water)
Layer Solute (Load) (kg/ha)
Layer Solute (Concentration) (mg/L soil-water)
Layer Solute (Concentration) (mg/kg soil)
Leachate Solute Concentration (mg/L soil-water)
Leachate Solute Load (kg/ha)
Rainfall Solute Concentration (mg/kg soil)
Irrigation Solute Concentration (mg/kg soil)
Rainfall Solute Load (kg/ha)
Irrigation Solute Load (kg/ha)

A11.2 Annual average summary outputs

These values are mostly represented as average annual values, except where indicated.

Water balance summary outputs (Total)
Rainfall (mm/yr)
Irrigation (mm/yr)
Runoff (mm/yr)
Soil Evaporation (mm/yr)
Transpiration (mm/yr)
Evapotranspiration (mm/yr)
Overflow (mm/yr)
Drainage (mm/yr)
Lateral flow (mm/yr)
Soil erosion (t/ha/yr)
Sediment delivery
Average sediment concentration in runoff
Runoff as percent of inflow
Evaporation as percent of Inflow
Transpiration as percent of Inflow
Drainage as percent of inflow
Potential evaporation as percent of inflow
Water balance summary “Crop” outputs
Crop rainfall (mm/yr)
Crop irrigation (mm/yr)
Crop runoff (mm/yr)
Crop soil evaporation (mm/yr)
Crop transpiration (mm/yr)
Crop evapotranspiration (mm/yr)
Crop overflow (mm/yr)
Crop drainage (mm/yr)
Crop lateral flow (mm/yr)
Crop soil erosion (t/ha/yr)
Crop sediment delivery
Fallow rainfall (mm/yr)
Fallow runoff (mm/yr)
Fallow soil evaporation (mm/yr)
Fallow drainage (mm/yr)
Fallow soil erosion
Fallow sediment delivery
Robinson index of erosion
Average fallow efficiency
Annual average cover
Average cover day before planting
Sediment EMC before DR
Sediment EMC before DR
Number of plantings (total)
Number of crops harvested (total)
Number of crops killed (total)
Average yield per harvest
Average yield per plant
Average yield per year
Yield divided by transpiration
Residue cover divided by transpiration
Irrigation “Ring Tank” summary
Annual ring tank irrigation losses
Annual ring tank irrigation losses delivered
Annual ring tank evaporation losses

Annual ring tank seepage losses
Annual ring tank overtopping losses
Annual ring tank runoff capture losses
Annual ring tank rainfall inflow
Annual ring tank additional inflow
Annual ring tank effective additional inflow
Annual ring tanks storage level
Annual ring tank prop days overflow
Annual ring tank prop years overflow
Pesticide summary
Pesticide application count
Product application
Average Pesticide Load in Water
Average Pesticide Load in Sediment
Average Total Pest Load
Days Greater Critical 1
Days Greater Critical 2
Days Greater Critical 3
Days Greater Critical 4
Average Bound Pest Concentration in Runoff
Average Unbound Pest Concentration in Runoff
Average Combined Pest Concentration in Runoff
Application Loss Ratio
Pest EMC
Phosphorus Summary
Particulate P concentration (mg/L)
Dissolved P concentration (mg/L)
Bioavailable Particulate P concentration (mg/L)
Bioavailable P concentration (mg/L)
Total P concentration (mg/L)
Particulate P export (kg/ha)
Dissolved P export (kg/ha)
Bioavailable Particulate P export (kg/ha)
Bioavailable P export (kg/ha)
Total P export (kg/ha)
EMC
Nitrate Summary
N03 N Store Bottom Layer (kg/ha)
N03 N Store Top Layer (kg/ha)
Total N Store Top Layer (kg/ha)
N03 N Load Leaching (kg/ha)
N03 N Load Runoff (kg/ha)
Particulate N Runoff (kg/ha)
Drainage For N03
Runoff_For_N03

A11.3 Monthly summaries

These summaries are calculate as monthly average values for each month of the year (i.e. there are 12 values for each output).

Water balance
Rainfall (mm)
Evaporation (mm)
Transpiration (mm)
Runoff (mm)
Drainage (mm)
Nitrate
Total N Store Top Layer (kg/ha)
N03 N Load Runoff (kg/ha)
N03 N Load Leaching (kg/ha)
Particulate N Runoff (kg/ha)
Drainage for N03
Runoff for N03
Monthly_N03_N_Store_TopLayer_kg_per_ha
Monthly_N03_N_Store_BotLayer_kg_per_ha
Solutes
Solute Load Soil (kg/ha)
Solute Export Leaching (kg/ha)
Solute Concentration Leaching (mg/L)

Appendix 12 – Initialisation routines

A12.1 Initialise climate data (called at start of each daily simulation)

At the start of simulation for each day, five variables are extracted from the SILO P51 file including:

- rain (used in water balance module)
- pan evaporation (used in water balance module)
- max and min temperatures (used in LAI vegetation module)
- solar radiation (used in LAI vegetation module)

Additionally, ETo is also read in, if it is available in the datafile (this is a recent addition to some SILO formats)

A12.2 Initialise crop parameters (called on first run)

- Set current crop indicator to crop 1
- Iterate through each crop and run its initialisation call
- Reset days_since_harvest, total_transpiration and total_evapotranspiration to 0.

A12.3 Initialise soil parameters (called on first run)

- Initialise all layer-based soil variables
- Sets all temporary soil parameters to zero
- Converts all soil layer limits (Air Dry, Saturation etc) from Volumetric (%) to “mm relative to wilting point”.
- Calculate PAW for each layer (based on initial PAW Input (%)).
- Calculate Total PAW
- Reset crop_residue, residue_cover and residue_cover_percent variables to 0;
- Calculate initial values of cumulate soil evaporatoin
- Calculate depth retention weighting factors
- Calculate drainage factors
- Calculate USLE_LS_Factor

A12.4 Calculate initial value of cumulative soil evaporation (called on first run)

This method calculates values of:

- sse1;
- sse2; and
- dsr

This looks at the first soil layer:

If DUL-PAW > Stage1SoilEvapLimit, then

$$sse1 = Stage1SoilEvapLimit \tag{A12.1}$$

$$sse2 = Maximum(0, DUL - PAW - Stage1SoilEvapLimit) \tag{A12.2}$$

Else,

$$sse1 = Maximum(DUL - PAW \tag{A12.3}$$

$$sse2 = 0 \tag{A12.4}$$

Then,

$$dsr = \left(\frac{sse2}{Cona}\right)^2 \tag{A12.5}$$

A12.5 Calculate USLE_LS_Factor (called on first run)

There are two calculation methods available for calculating "usle_ls_factor" including the original ***PERFECT*** methodology, and one developed by ***HowLeaky*** developers (source unknown).

If using the ***PERFECT*** methodology:

$$aht = \frac{fieldslope \times slopelength}{100} \tag{A12.6}$$

$$lamda = 3.281 \times \sqrt{slopelength^2 \times aht^2} \tag{A12.7}$$

$$theta = \operatorname{asin}\left(\frac{aht}{slopelength}\right) \tag{A12.8}$$

If the $fieldslope$ < 9.0, then

$$usle\_ls\_factor = \frac{lamda^{\left(\frac{RillRatio}{1+RillRatio}\right)}}{76.2} \times (10.8 * \sin(theta) + 0.03) \quad \text{A12.9}$$

else

$$usle\_ls\_factor = \frac{lamda^{\left(\frac{RillRatio}{1+RillRatio}\right)}}{76.2} \times (16.8 * \sin(theta) - 0.5) \quad \text{A12.10}$$

If using the revised ***HowLeaky*** methodology:

$$usle\_ls\_factor = \frac{slopelength^{\left(\frac{RillRatio}{1+RillRatio}\right)}}{22.1} \times (0.065 + 0.0456 \times fieldslope + 0.006541 * fieldslope^2) \quad \text{A12.11}$$

A12.6 Calculate depth retention weighting factor (called on first run)

This method calculates the depth retention weighting factor “wf” value for each layer i:

$$a = -4.16 \times \left(\frac{depth_i}{depth_{i-1}}\right) \quad \text{A12.12}$$

$$b = -4.16 \times \left(\frac{depth_{i+1}}{depth_{i-1}}\right) \quad \text{A12.13}$$

$$wf_i = 1.016 * \left(\frac{e^a}{e^b}\right) \quad \text{A12.14}$$

A12.7 Calculate drainage factors (called on first run)

These calculations differ slightly from the original ***PERFECT*** code as $Ksat$ was treated differently in ***PERFECT*** (Assumed 12hr day).

For each layer:

$$swcon_i = \frac{2 \times ksat_i}{SatLimit_i - DUL_i + ksat_i} \quad \text{A12.15}$$

A12.8 Apply resets if any (called at start of daily simulation)

Checks for:

- Reset Soil Water at date
- Reset Crop Residue at date

A12.9 Set start-of-day parameters (called at start of daily simulation)

- Reorder crop list so that current crop is first.
- Set effective_rain=rain
- Set swd, satd, irrigation_amount and irrigation_applied to 0
- Iterate through each layer (i) and calculate satd (saturation deficit) and swd (soil water deficit):

$$satd = satd + (SatLimit_i - PAW_i) \tag{A12.16}$$

$$swd = satd + (DUL_i - PAW_i) \tag{A12.17}$$

- Set roughness_ratio and tillage_residue_reduction to 0

A12.10 S-Curve initialisation

This subroutine fits an s curve to two points. It was from EPIC3270.

$$value1 = LAICurveX1/LAICurveY1 - LAICurveX1 \tag{A12.18}$$

$$value2 = LAICurveX2/LAICurveY2 - LAICurveX2 \tag{A12.19}$$

$$x = log(value1) \tag{A12.20}$$

$$value1 = LAICurveX1/LAICurveY1 - LAICurveX1 \tag{A12.21}$$

$$LAICurveY2active = \frac{x - log(value2)}{LAICurveX2 - LAICurveX1} \tag{A12.22}$$

$$LAICurveY1active = x + LAICurveX1 * LAICurveY2active \tag{A12.23}$$

Appendix 13 – Model soil cracking

This function allows for water to directly enter lower layers of the soil profile through cracks. For cracks to occur the and second profile layers must be less than 30% and 50% respectively of field capacity. Cracks can extend down the profile using similar criteria. This subroutine assumes cracks must exist at the surface. Water is placed into lowest accessible layer first.

Firstly, we initialise total water redistributed through cracks (tred).

$$tred = 0 \tag{A13.1}$$

For each Layer "i" the redistributable amount (red_i) is:

$$red_i = 0 \tag{A13.2}$$

$$mcfc_i = \frac{PAW_i}{DUL_i} \tag{A13.3}$$

Where $mcfc_i$ is constrained between 0 and 1. Then check to see if there was significant rainfall (>10mm), otherwise don't continue. If rainfall is enough, then check the number of depths (nod) "in sequence" for cracking to occur (counting stops if condition fails):

$$nod = Count(mcfc_i < 0.3) \tag{A13.4}$$

Then fill cracks from lowest cracked layer first to a maximum of 50% of field capacity. First calculate the total amount of redistributable water (tred):

$$tred = Maximum(MaxInfotIntoCracks, effective\_rain) \tag{A13.5}$$

Then iterating backwards from nod-1 to 0, we calculate red_i by distributing water from the tred bucket:

$$red_i = Minimum\left(tred, \frac{DUL_i}{2} - PAW_i\right) \tag{A13.6}$$

For each iteration, recalculate tred (what water is remaining)

$$tred = tred - red_i \tag{A13.7}$$

Then we calculate effective rainfall after infiltration into cracks (not that redistribution of water into layer 1 is ignored).

Appendix 14 - LAI model day-length calculations

This function calculates day length from latitude and day number in the year.

$$sund = -2.2 \tag{A14.1}$$

$$theta = 0.0172142 \times (day\_no - 172.0) \tag{A14.2}$$

$$\begin{aligned} sdcln = 0.00678 + 0.39762 \times cos(theta) + 0.00613 \times sin(theta) \\ - 0.00661 \times cos(2.0 \times theta) - 0.00159 \times sin(2.0 \times theta) \end{aligned} \tag{A14.3}$$

$$dcln = asin(sdcln) \tag{A14.4}$$

$$rlat = latitude \times 0.0174533 \tag{A14.5}$$

$$dnlat = -\frac{sin(rlat)}{cos(rlat)} \times \frac{sin(dcln)}{cos(dcln)} \tag{A14.6}$$

$$rsund = sund \times 0.0174533 \tag{A14.7}$$

$$twif = cos(rlat) \times cos(dcln) \tag{A14.8}$$

$$atwil = \frac{sin(rsund)}{twif} \tag{A14.9}$$

$$htwil = acos(atwil + dnlat) \tag{A14.10}$$

$$day\_length = 7.639437 \times htwil \tag{A14.11}$$