OVERSEER® Technical Manual

Technical Manual for the description of the OVERSEER®
Nutrient Budgets engine

ISSN: 2253-461X

Hydrology

November 2021

Prepared by D M Wheeler

AgResearch Ltd

DISCLAIMER: While all reasonable endeavours have been made to ensure the accuracy of the investigations and the information contained in this Technical Manual, OVERSEER Limited gives no warranties, representations or guarantees, express or implied, in relation to the quality, reliability, accuracy or fitness for any particular purpose, of the information, technologies, functionality, services or processes, described in this Technical Manual, nor does it make any warranty or representation that this Technical Manual or any information contained in this Technical Manual is complete, accurate or not misleading. OVERSEER Limited expressly disclaims and assumes no liability contingent or otherwise, that may arise from the use of, or reliance on, this Technical Manual including as a result of but not limited to, any technical or typographical errors or omissions, or any discrepancies between this Technical Manual and OVERSEER® Nutrient Budgets. The contents of this Technical Manual may change from time to time without notice at the discretion of OVERSEER Limited.

COPYRIGHT: You may copy and use this report and the information contained in it so long as your use does not mislead or deceive anyone as to the information contained in the report and you do not use the report or its contents in connection with any promotion, sales or marketing of any goods or services. Any copies of this report must include this disclaimer in full.

Copyright © 2021 OVERSEER Limited

Published by:

OVERSEER Limited

http://www.overseer.org.nz

OVERSEER® is a registered trade mark owned by the OVERSEER owners

The OVERSEER owners are:

Ministry for Primary Industries (MPI), Fertiliser Association of New Zealand Inc. (FANZ) and AgResearch Ltd (AgResearch).

Preface

OVERSEER® Nutrient Budgets

OVERSEER® Nutrient Budgets (OVERSEER) is a strategic management tool that supports optimal nutrient use on farm for increased profitability and managing within environmental limits.

OVERSEER provides users with information to examine the impact of nutrient use and flows within a farm and off-farm losses of nutrients and greenhouse gases. An OVERSEER nutrient budget takes into account inputs and outputs and the key internal recycling of nutrients around the farm.

See the OVERSEER website for more detailed information: http://www.overseer.org.nz

This technical manual

OVERSEER is made up of a user interface and an engine. These two components work together to enable users to generate nutrient budget reports. The Technical Manual provides details of the calculation methods used in the OVERSEER engine.

The OVERSEER engine is based on extensive published scientific research. Technical information about the model's development and use can be found in a growing number of conference proceedings and peer-reviewed papers. Given the ongoing upgrades many of the earlier papers no longer reflect the current version.

The Technical Manual chapters provide detailed descriptions of the methods used in the OVERSEER engine's main sub-models. The Technical Manual sets out the underlying principles and sources of data used to build the model engine. It is a description of the model as implemented, and hence references may not now be the most appropriate or cover the range of data of information currently available, or may not necessarily be the most up to date. If the source of some information and/or assumptions is not known or could not be found, this is acknowledged.

The chapters will continually be updated to reflect the current version.

If readers have feedback or further technical information that they consider could contribute to the future development of the model, please provide feedback via the website http://www.overseer.org.nz.

Scientific contribution to model development:

OVERSEER is a farm systems model covering a wide range of science disciplines. Since the model's inception, a large number of researchers from many disciplines and organisations have contributed to its development.

Researchers contributing significantly to the hydrology component of the model described in this report include:

Kit Rutherford, NIWA Ltd

David Wheeler, AgResearch Ltd

John Bright, Aqualinc

Lucy McKergow, NIWA Ltd

David Rupp, NIWA Ltd

Ross Woods, NIWA Ltd

Jochen Schmidt, NIWA Ltd

Contents

Hydrology

1. Introduction

1.1. Background

The hydrology sub-model was originally designed to provide input into the wetland and riparian strip sub-model (Rutherford *et al*., 2008), which required daily flow rates as the efficiency of these features is flow dependent. The hydrology sub-model was extended to calculate drainage used in monthly sub-models such as N leaching and annual sub-models for other nutrient leaching. Outputs are also provided for other sub-models, for example, water-filled pore space used in the nitrous oxide sub-model, and soil water contents for pasture and crop growth sub-models.

The relationship between chapters of the technical manual and the hydrology sub-model is shown schematically in Figure 1. Thus, this document should be read in conjunction with other chapters. In particular, the hydrology sub-model is dependent on climate and soil data that is described in the Climate and Characteristics of soil chapters.

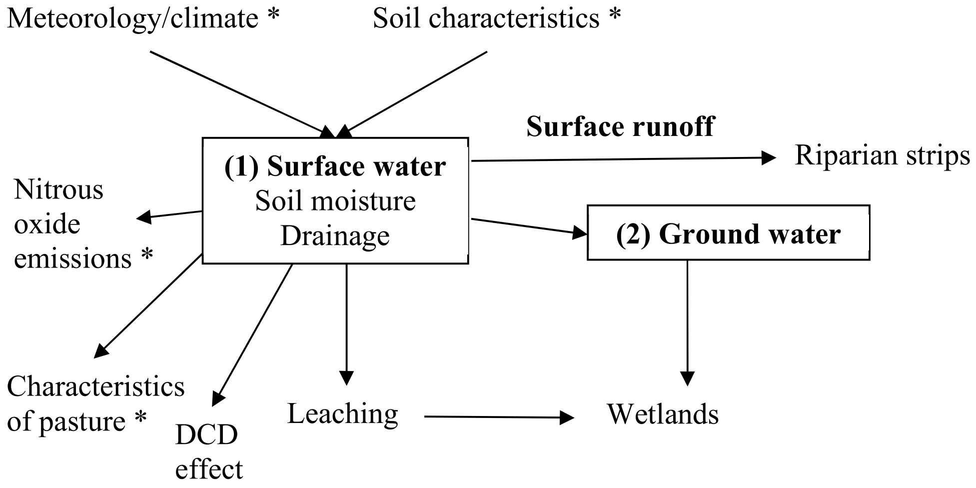

Figure 1. Relationship between sub-model sections and the hydrology sub-model (* are Technical manual chapters). The hydrology sub-model consists of: (1) surface water and (2) ground water sub-models.

The conceptual model of hydrology in a wetland catchment is shown in Figure 2. This concept was originally developed by National Institute of Water and Atmosphere (NIWA) and is described in detail by Rutherford *et al*. (2008), and Rutherford and Wheeler (2011). These papers include the data for formulating and validating the sub-model. This section records how this sub-model has been implemented at a block and farm scale, and salient background information. Thus, the hydrology sub-model consists of the surface water and ground water model (Figure 2).

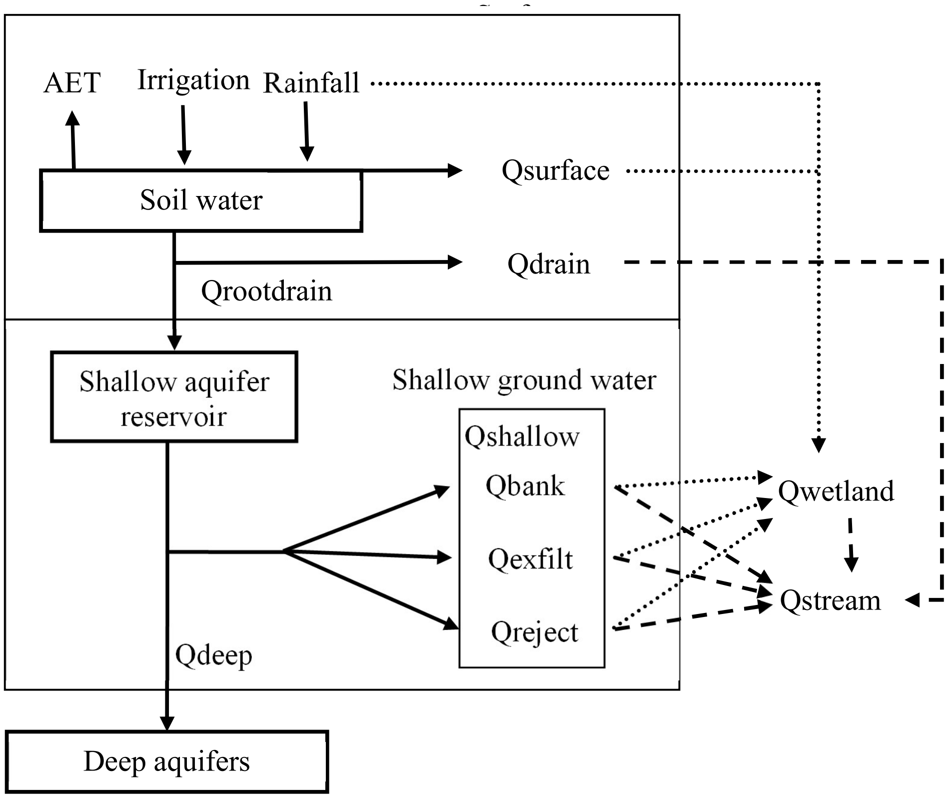

Figure 2. Conceptual hydrology model showing surface water and ground water sub-models, where Q is flow (m^3). Dotted lines indicate contributory sources. See text for definition of the terms.

The hydrology model is separated into two sub-models (Figure 2). The first is the surface water sub-model has the following components (with sections that refer to the daily calculation in parenthesis):

Soil water	surface water reservoir (section 3.1), that is, the water held in the soil.
Qsurface	surface flow caused by low infiltration rates or saturation soil profile (section 3.5).
Qrootdrain	flow from the base of the root zone (section 3.6).
Qdrain	flow removed by mole-tile or field drainage system. This directly enters streams (section 5.1).

The shallow ground water model estimates re-emergent flows in wetlands and riparian strips, and includes the following components:

Reservoir	reservoir is an aquifer that receives flow from the root zone (Qrootdrain). Water leaves the reservoir via deep flow (Qdeep), or shallow flow (Qshallow) that re-emerges (section 4.2.1).
Qdeep	flow to deep aquifers (section 4.2.2).
Qshallow	shallow flow to groundwater that emerges on the property.

The shallow flow consists of three components:

- QBanks flow to seepage (section 4.2.4).
- Qexfilt flow from the saturation part of the aquifer (section 4.2.5)
- Qreject flow that occurs when aquifer is saturated (section 4.2.6).

The flow from each of the shallow flow component contributes to wetlands or stream flows on the property:

- Qstreams part of shallow flow that flows directly to streams.
- Qwetlands part of shallow flow that emerges in or upstream of wetlands.

1.2. Workings of the technical manual

The aim of the technical manual is to provide a level of detail so that users of OVERSEER can clearly see the underlying principles and sources of data used to build the components of the model. This technical chapter is part of a series of technical manuals currently under development to explain the inner working of the OVERSEER engine.

In the equations in this manual, units are shown using ( ) and cross-references other equations and sections within this manual or to other chapters of the technical manual are shown using [ ]. Equations with multiple '=' options are cascading alternatives in the order they are considered. The condition is shown on the right hand side. The variable and parameter names used are generally shortened names of the property, and this naming convention is similar to the convention used in the OVERSEER engine model.

1.3. Abbreviations and subscripts

Abbreviations

AET	Actual evapotranspiration (mm).
Q	flow (m^3/day).
PET	Potential evapotranspiration (mm).
RO	area specific yield of water (mm/day) [section 1.4].
SM	soil moisture (water) content (mm).

Subscripts:

block	block created for a farm.
mon	month of calendar year (January to December).

Within equations, units are shown using ( ) and cross-references to other chapters of the technical manual or sections within this document are shown using [ ]. Equations with multiple '=' options are cascading alternatives in the order they are considered. The condition is shown on the right hand side. The variable and parameter names are generally shortened names of the property, and this naming convention is similar to the convention used in the OVERSEER engine.

1.4. Definition of runoff

In the hydrology sub-model, runoff (RO) is defined as an area specific yield of water. This is equivalent to rainfall being expressed as mm/day. Runoff may be surface or subsurface. For each runoff, there is a corresponding flow (Q). The two are related as shown in Equation 1 and 2.

Equation 1: $Q = (RO / 1000) * Area * 10000$

and

Equation 2: $RO = Q / Area / 10000 * 1000$

Q is the flow (m^3/day).
RO is the area specific yield (mm/day).
1000 is the conversion mm/m.
Area is area runoff comes from (ha).
10000 is the conversion m^2/ha.

In farming terms, runoff frequently refers to hydrology surface or overland runoff. Drainage has many definitions including runoff below the root zone, the existence of mole/tile drains or other drainage systems, or the ability of surface water to move from the soil surface under high rainfall. Seepage usually refers to re-emergent subsurface runoff (Qwetland).

1.5. Relationship with nutrient movement

When water moves, nutrients also move. The amounts and rates of nutrient movement are covered in separate chapters, which refer to either the flow (Q) or area specific yield (RO) in Figure 2. The mitigation options that can be applied to reduce nutrient movements vary with the component as shown in Table 1.

Table 1. Component of drainage and mitigation options that can be used

Component	Mitigation options
surface	contour grass and riparian strips. Sometimes re-infiltrates on hill slopes.
drainage system	artificial wetlands.
shallow	fencing and stock management, wetland enhancement.
wetlands	fencing and stock management, wetland enhancement.
streams	bypass filters and wetlands.

1.6. Computational time step

OVERSEER computes monthly nutrient loads for N or annual nutrient loads for other nutrients. In reality, water and nutrient flows vary at time scales of minutes to decades. For example:

- infiltration-excess surface flow occurs only during heavy rainfall,

- saturation-excess surface flow is initiated by heavy rainfall but persist for days-weeks after rainfall has stopped,
- drainage from the root zone to groundwater is usually negligible in summer and increases during autumn-winter,
- flow from shallow groundwater that re-emerges on the property persists for weeks–months but may cease during droughts, and
- spring flow from deep groundwater persists throughout the year but may vary over years–decades with long-term cycles in rainfall.

The ability of filter strips and wetlands to remove or store nutrients is strongly flow dependant. Filter strips only receive inflows during surface runoff (time-scale minutes-hours). They may trap a substantial fraction of incoming particulates when inflows are moderate, but can be overwhelmed by large flows leading to decreased effectiveness. Wetlands are fed by re-emerging shallow sub-surface flow (time-scale days-weeks-months) and surface flow during rainfall events (time-scale minutes-hours). They may remove a substantial proportion of the incoming nitrate-nitrogen load during low flows when the soil-water contact times are long. However, as inflow rates increase, surface flow tends to by-pass the active soils and the removal efficiency decreases.

An annual time-step is inappropriate for simulating the majority of nutrient removal processes. A weekly or monthly time step may suffice for modelling seepage or spring-fed wetlands, although surface runoff often causes short-term reductions in removal efficiency. A daily time step does not capture the fine detail of short-term variations in rainfall and surface runoff. However, hourly or sub-hourly calculations would require extensive input data and cannot be accommodated within OVERSEER. A daily time step was selected as a useful compromise. Thus, the hydrology sub-model uses a daily time step, with results summed or averaged as required for other parts of the OVERSEER engine.

2. Inputs

Properties from soil and climate sub-models are required to run the hydrology sub-model.

2.1. Soil properties

2.1.1. Soil water contents

The hydrology sub-model requires SM contents at wilting point, field capacity, and saturation (SMfc, SMwp, and SWsat respectively). These are defined as part of the soil properties section, which returns soil water contents at 100 mm intervals down the profile (Characteristics of Soils chapter of the Technical Manual).

The hydrology sub-model requires soil water contents at 600 mm or the depth to the impeded layer, whichever is smaller (SMfc600, SMwp600, and SWsat600), to the rooting depth of the crop (SMfcrd, SMwprd, and SWsatrd), and to 100 mm (SMfc100, SMwp100 and SWsat100) which is the first soil layer. Note that the pastoral and cut and carry sub-models are based on 600 mm depth.

2.1.2. Profile and crop available water (PAW, CAW)

Profile available water (depth) (PAW_D), previously referred to as available water capacity (AWC), is the rainfall equivalent depth of 'total available water' within a specified depth D in the soil (Irrigation New Zealand, 2014). It is soil specific and independent of plant type or root depth. Total available water is extractable by plants (plant type may be specified); taken as the difference between soil water at field capacity and at permanent wilting point (Irrigation New Zealand 2014). Thus:

Equation 3: $PAW_D = \sum_z (SMfc_z - SMwp_z)$

D is the depth of interest.
SMwp is the wilting point (mm) of the layer z.
SMfc is the field capacity (mm) of the layer z.

where z is the number of 100 mm (10 cm) layers down to the profile depth. For the main drainage calculations z is 6 (to 600 mm depth, PAW_{60}).

Total available water is also calculated to the rooting depth in the rainfall equivalent depths to give CAW_D (crop available water). For pastoral systems, the rooting depth is constant over time. CAW to the rooting depth (CAW_{60}) is the same as PAW_{60}, unless the maximum rooting depth is entered, in which case it is CAW to the maximum rooting depth. For crops, CAW to rooting depth varies with the crop and stage of growth. Thus on sowing z is typically < 3 (< 300 mm), and can extent to 15 (1500mm) depending on the crop.

2.1.3. Additional soil properties

The soil properties are detailed in the Characteristics of Soils chapter of the Technical Manual. The following properties are required for the hydrology sub-model:

- Natural profile drainage class
- Pugging occurrence
- Current profile drainage class
- Saturated hydraulic conductivity (m/day)
- Top soil (< 100 mm) clay content
- Sub soil clay contents (%)
- Saturated conductivity (mm/day)

2.2. Climate data

Climate data to drive the hydrology sub-model is outlined in the Climate section of the Technical Manual. The inputs required are:

- Rainfall – daily rainfall (mm/day).
- PET - daily PET (mm/day).
- Snow melt (mm rainfall equivalent/month).

2.3. Irrigation inputs

2.3.1. Irrigation system types

Irrigation system types are based on the physical apparatus used to apply the water. The irrigation sub-model uses irrigation system types primarily to set default data for management options (section 2.3.5), and to estimate additional drainage and atmospheric losses (3.3.4). The irrigation system type options are:

- Linear and centre pivot
- Travelling irrigator
- Spraylines
- Micro-irrigation (drip and sprinkler)
- Solid set
- Controlled flood
- Border dyke

These align with common irrigation systems types used in New Zealand as described by Irrigation New Zealand (Irrigation New Zealand 2014).

2.3.2. Input options

The irrigation input options are:

- Irrigation scheduling. The options are defined in section 2.3.3.
- Frost protection, where the average frost (°C), average duration of the frost (hours), and the number of days of frost each month are entered. This option is available as a specific month input.
- Application depth, where a fixed depth is applied each month. The application depth should be aligned with the climate data otherwise unusual irrigation and drainage results can occur. No other inputs are required. This option is available as a specific month input.

Only one option can be used for a given month. Frost protection is only shown for fruit crop blocks. Frost protection and application depth is not shown for setting up multiple months.

2.3.3. Irrigation scheduling

Irrigations scheduling is based on depth per application and frequency (return period), and whether they vary according to soil water contents or are fixed. If soil water content monitoring is used, then soil water contents are used to determine whether an irrigation event is triggered, hence a variable return period between irrigation events. The difference between the trigger point and the target (section 2.3.3.3) determines how much water is applied, hence a variable application depth. The available strategies are summarised in Table 2.

Table 2. Irrigation scheduling strategies. The first letter in the strategy code refers to whether depth per application is fixed or variable, and the second whether return period is fixed or variable.

Strategy code	Soil water contents use to set:	Fixed
FF		Depth per application Return period
FV	Trigger point	Depth per application
VF	Depth applied to achieve target	Return period
VV	Trigger point Depth applied to achieve target	

2.3.3.1. *Irrigation scheduling strategies*

The options for selecting how soil moisture contents are used are:

- Fixed depth and return period
- Visual assessment/dig a hole
- Soil water budget
- Soil moisture sensors: Probes
- Soil moisture sensors: Tapes

If the option 'Fixed depth and return period' or 'Visual assessment/dig a hole' is selected, then the scheduling strategy is fixed depth per application and fixed return period. If the options 'Soil water budget', 'Soil moisture sensors' are selected, then 'Strategy' is shown with the options:

- Trigger point; fixed depth applied
- Depth applied to achieve target; fixed return period
- Trigger point and depth applied to achieve target

The options 'Soil water budget' and 'Soil moisture sensors' are present to shown the method of monitoring used, but these have no effect on the rest of the irrigation sub-model.

2.3.3.2. *Input data*

The scheduling strategies modify the input data required as shown in Table 3.

Table 3. Inputs for each irrigation scheduling strategy used to estimate the depth irrigation applied.

Scheduling strategy	Inputs (* = optional)
Fixed depth and return period	Depth per application (mm/application) Return period (days)
Trigger point; fixed depth applied	Depth per application (mm/application) Minimum return period (days) * Trigger point[1]
Depth applied to achieve target; fixed return period	Minimum application depth (mm/application) * Maximum application depth (mm/application) * Return period (days) Target[1]
Trigger point and depth applied to achieve target	Trigger point [1] Target[1]

[1] Section 2.3.3.3

2.3.3.3. *Trigger point and target*

Trigger point is defined as the soil water content, expressed as '% of PAW' or 'mm deficit', that initiates an irrigation event.

Target is the soil water content, also expressed as '% of PAW' or 'mm deficit', that irrigation is applied to achieve. This is sometimes referred to as the refill point.

2.3.3.4. *Controlled flood and border dyke*

For controlled flood and border dyke systems, the only strategy allowed is fixed depth per application and return period. These can be user-defined or for default values (section 2.3.5) are used.

For border dyke, an option for management of border dyke outwash is required, with options of 'Outwash occurs' (the default) and 'No outwash'.

2.3.4. Management system definition

For all irrigation scheduling option system types, there is the option to use default values, or for the user to provide input values. In many cases, default values are dependent on PAW_{60}. The default or chosen values are shown in an irrigation report.

Management system definitions have the following options:

- 'Default 1 shift per day' and 'Default 2 shifts per day' for travelling irrigator and Sprayline method of application, or 'Default' for all other irrigation system types.
- User defined for all irrigation system types.

If a default option is selected, then no additional input is displayed as the default depth of application, return period and trigger point are dependent on soil profile available water content to 60 cm (PAW_{60}). PAW_{60} is calculated at run time from the relevant inputs. Irrigation default values are shown in the irrigation report.

2.3.5. Default data inputs

2.3.5.1. *Depth per application and return period*

The default depth per application and return period are shown in Table 4. The default values are based on industry experience gained across a number of modelling studies for a 'Depth applied to achieve target; fixed return period' system (J Bright, Aqualinc, pers. comm.).

Table 4. Default depth per application and return period

Irrigation system type	Condition	Depth per application (mm/application)	Return period (days)
Linear and centre pivot	PAW_{60}[1] < 55	15	3
	$55 \le PAW_{60} < 75$	22	4
	$PAW_{60} \ge 75$	25	5
Travelling irrigator[2]	$PAW_{60} < 65$	45	6
	$65 \le PAW_{60} < 75$	50	7
	$75 \le PAW_{60} < 85$	50	8
	$85 \le PAW_{60} < 95$	55	9
	$95 \le PAW_{60} < 110$	55	10
	$PAW_{60} \ge 110$	60	12
Spraylines	2 Shifts per day	33	7
	1 Shift per day	65	14
Micro-irrigation (drip and sprinkler)		65	7
Solid set		65	7
Controlled flood		85	14
Border dyke		85	14

[1] PAW_{60} is the Profile available water to 600 mm depth (section 2.1.2).

[2] values are for default option of '1 shift per day'. For the option '2 shifts per day', the values are the integer value of half the '1 shift per day' values.

2.3.5.2. *Minimum return period*

The default minimum return periods are shown in Table 5. Minimum return periods are not an input for controlled flood or border dyke systems (section 2.3.3.4) and hence were not set.

Table 5. Default minimum return period.

Irrigation system type	Minimum return period (days)
Linear and centre pivots	3
Travelling irrigator	5
Spraylines	3
Micro-irrigation (drip and sprinkler)	5
Solid set	5
Controlled flood	n/a
Border dyke	n/a

2.3.5.3. *Minimum depth per application*

The default minimum depth per application is shown in Table 6. Minimum depths per application are not an input for controlled flood or border dyke (section 2.3.3.4) and hence were not set.

Table 6. Default minimum depth per application.

Irrigation system type	Minimum depth per application (mm/application)
Linear and centre pivots	5
Travelling irrigator	10
Spraylines	5
Micro-irrigation (drip and sprinkler)	10
Solid set	10
Controlled flood	n/a
Border dyke	n/a

2.3.5.4. *Maximum depth per application*

The default maximum depth per application is shown in Table 7. Maximum depth per application is not an input for controlled flood or border dyke usually (section 2.3.3.4) and hence was not set.

Table 7. Default maximum depth per application.

Irrigation system type	Maximum depth per application (mm/application)
Linear and centre pivots	40
Travelling irrigator	60
Spraylines	40
Micro-irrigation (drip and sprinkler)	60
Solid set	60
Controlled flood	n/a
Border dyke	n/a

2.3.5.5. *Trigger point*

Default values for trigger point are shown in Table 8. The default values are based on industry experience gained across a number of modelling studies for a 'Depth applied to achieve target; fixed return period' system (J Bright, Aqualinc, pers. comm.). Trigger point values is not an input for controlled flood or border dyke systems (section 2.3.3.4) and hence values were not set.

Table 8. Default trigger point values.

Irrigation system type	Condition	Trigger point (% of PAW_{60})
Linear and centre pivot	PAW_{60}[1] < 65	50
	$65 \leq PAW_{60} < 75$	53
	$75 \leq PAW_{60} < 85$	56
	$85 \leq PAW_{60} < 95$	61
	$95 \leq PAW_{60} < 110$	63
	$110 \leq PAW_{60} < 130$	67
	$130 \leq PAW_{60} < 150$	70
	$PAW_{60} \geq 150$	71
Travelling irrigator	$PAW_{60} < 105$	50
	$105 \leq PAW_{60} < 125$	62
	$125 \leq PAW_{60} < 145$	67
	$PAW_{60} \geq 145$	72
Spraylines	2 Shifts per day: $PAW_{60} < 45$	50
	$45 \leq PAW_{60} < 55$	55
	$PAW_{60} \geq 55$	60
	1 Shift per day: $PAW_{60} < 125$	50
	$125 \leq PAW_{60} < 145$	55
	$PAW_{60} \geq 145$	60
Micro-irrigation (drip and sprinkler)	$PAW_{60} < 45$	50
	$45 \leq PAW_{60} < 55$	55
	$PAW_{60} \geq 55$	60
Solid set	$PAW_{60} < 45$	50
	$45 \leq PAW_{60} < 55$	55
	$PAW_{60} \geq 55$	60
Controlled flood	n/a	n/a
Border dyke	n/a	n/a

[1] PAW_{60} is the Profile available water to 600 mm depth (section 2.1.2).

2.3.5.6. *Target*

Default values for the target are shown in Table 9. Target is not an input for controlled flood or border dyke systems (section 2.3.3.4) and hence were not set.

Table 9. Default target values.

Irrigation system type	Target (% PAW_{60})
Linear and centre pivot	95
Travelling irrigator	95
Spraylines	95
Micro-irrigation (drip and sprinkler)	95
Solid set	95
Controlled flood	n/a
Border dyke	n/a

[1] PAW_{60} is the Profile available water to 600 mm depth (section 2.1.2).

2.4. Other inputs

2.4.1. Evaporation factor

Evaporation factor (k_evapo) is a coefficient which accounts for the capability of soil to supply water for evaporation, which is usually restricted in summer as defined for the monthly water balance method for the crop sub-model (Cichota *et al*., 2010). k_evapo has the monthly values of 0.5657, 0.5404, 0.7035, 0.7136, 0.9813, 1.00, 1.00, 1.00, 0.9506, 0.7831, 0.6909, and 0.6133 for January to December.

2.4.2. Topography and average hill slope

Average hill slope is dimensionless and is estimated as shown in Equation 4.

Equation 4: hillslope = tan(slopedegree * pi /180)

slopedegree = 4, 11, 21, 31° for flat, rolling, easy hill and hard hill respectively.

3. Daily soil water

Total runoff (surface and below the root zone) is determined daily from a simple soil water accounting model (Porteous *et al*., 1994) for pastoral, cut and carry, fodder crop, cropping and fruit crop blocks on the farm. The same common soil water model is used for all block types, although there are some differences in methods as outlined in the following sections.

Each day, up to four SM contents are calculated, namely:

- soil water content to top 600 mm or the depth to the impeded layer, whichever is the smaller, on a daily basis (section 3.1.3). This is used for determine irrigation depths. The drainage from this depth is used in most calculations within the OVERSEER engine.
- soil water for the whole profile down to maximum rooting depth on a daily basis (section 3.1.1). This is mainly used to determine transpiration rates.
- top 100 mm (section 3.1.2) on a daily basis. This is used as a modifier for evaporation rates.
- soil water content and drainage to 300 mm on a monthly basis, with drainage used in the DCD sub-model.

The hydrology sub-model provides daily estimates of surface runoff, drainage from the root zone, and daily inputs section 3.1.5 for the hydrology component of the wetland and riparian strip sub-models, if these features are used. Water filled pore space is also estimated daily for use in the nitrous oxide sub-model (see Nitrous oxide emissions chapter of Technical Manual).

The hydrology sub-model also sums daily estimates of rain and irrigation inputs, AET, surface runoff, drainage and outwash losses to provide monthly estimates. These are used in other parts of the OVERSEER engine as indicated in Figure 1.

3.1. Soil water

The daily soil water contents are estimated for two years for pastoral, cut and carry and fruit crop blocks, starting on January 1. The first year is used to initialise the soil water content, and the hydrology sub-model uses the second year's data for calculations.

For crops, a 3-year cycle is initialised starting on January 1. Soil water content is estimated from the beginning of the start month on the grid (user defined), running for two years. Thus, the soil water outputs in the reporting year are for the twelve months prior to and including the end of the crop inputs.

Soil water contents and hence drainage is calculated to 600mm, and to the profile depth (1500mm for lucerne and crops)

3.1.1. Soil water in top 600 mm

Soil water for the soil profile to 600 mm, or to the depth of the impeded layer if this is less than 600 mm, (SM600; mm) is estimated as:

Equation 5: $SM600_t = SM600_{t-1} + DailyInput + DailyIrrigation - AET – ROsurface – ROdrain600$

$SM600_t$ is the soil water content (mm) to 600mm on day t.

DailyInput is the daily rainfall, irrigation and snow melt (mm/day) [section 3.1.5].

DailyIrrigation is daily irrigation (mm/day) [section 3.3.3].

AET is the actual evaportransipation (mm/day) [section 3.4].

ROsurface600 is the surface runoff (mm/day) [section 3.5].

ROdrain600 is the drainage from root zone (mm/day) [section 3.6].

Soil water contents are likely to be higher in winter than summer. To reflect this, initialise soil water content at time 0 ($SM600_0$) is set as:

Equation 6: $SM600_0 = SMwp600 + (PAW600 * k\_evapo_{mon})$

SM600wp is the soil water content at wilting point to 600 mm [section 2.1.1].

PAW600 is the plant available water to 600 mm (mm) [section 2.1.2].

k_evapo is a coefficient to account for the capability of soil to supply water for evaporation [section 2.2].

mon is the month the soil water calcuations start.

3.1.2. Soil water content in top 100 mm

The soil water content in the top 100 mm of the soil profile ($SM100_{t;}$ mm) is used in the evaporation sub-model (section 3.4.2). It is assumed that daily inputs, evaporation and surface runoff is the same as for the 600 mm soil water calculations. Drainage is not estimated as it is assumed that SM100 cannot exceed soil water content (mm) at field capacity of the first 100 mm layer. Thus, SM100 is calculated as:

Equation 7: SM100t = SM100t-1 + DailyInput + DailyIrrigation - Wevapo – Wtransp100 - ROsurface

DailyInput is the daily rainfall (mm/day) [section 3.1.5].

DailyIrrigation is daily irrigation (mm/day) [section 3.3.3].

Wevapo is the evaporation (mm/day) [section 3.4.2].

Wtransp100 is the transpiration from a top 10 mm layer (mm/day) [*Equation 8*].

ROsurface is the surface runoff (mm/day) [section 3.5].

Root density is higher in the top of the soil profile, and transpiration will be higher than the profile average. Thus it was assumed transpiration removal was 1.4 that of transpiration at 600 mm depth, that is:

Equation 8: Wtransp100 = Wtransp600 * 1.4

Wtransp is the transpiration (mm/day) to 600 mm depth [section 3.4.1].

1.4 recognises that the root density is higher in the top of the soil profile, and transpiration will be higher than the profile average.

SM10 is constrained such that:

Equation 9: $SM100wp <= SM100_t <= SM100fc$

$SM100_t$ is the soil water content (mm) in the top 100 mm of the soil profile

SM100wp is the soil water content (mm) at wilting point of the first 100 mm layer.

SM100fc is the soil water content (mm) at field capacity of the first 100 mm layer.

To initialise the soil water content, soil water content to 100 mm at time 0 ($SM10_0$) is estimated as:

Equation 10: $SM100_0 = SMwp100 + (SMfc100- SMwp100) * k\_evapo_{mon}$

SMwp100 is the soil water content (mm) at wilting point of the first 100 mm layer.

SMfc100 is the soil water content (mm) at field capacity of the first 100 mm layer.

k_evapo is a coefficient to account for the capability of soil to supply water for evaporation [section 2.2].

3.1.3. Soil water to profile depth

If the profile depth is 600 mm (for example on pastoral blocks) then SMpd, ROsurfacepd, and ROrootdrainpd (soil water content, surface runoff and drainage to the profile depth) are the same as SM600, ROsurface600 and ROrootdrain600 (soil water content, surface runoff and drainage to 600 mm depth) respectively.

Otherwise, soil water contents for the profile is estimated assuming that daily inputs, irrigation, evaporation and transpiration, and surface runoff are the same as at 600mm. Thus:

Equation 11: $SMpd_t = SMpd_{t-1} + DailyInput + DailyIrrigation - AET – ROsurface – ROdrainpd$

$SMpd_t$ is the soil water content (mm) to the profile depth on day t

DailyInput is the daily rainfall, irrigation and snow melt (mm/day) [section 3.1.5].

DailyIrrigation is daily irrigation (mm/day) [section 3.3.3].

AET is the actual evaportransipation (mm/day) [section 3.4].

ROsurface is the surface runoff (mm/day) [section 3.5].

ROdrainpd is the drainage from root zone (mm/day) [section 3.6]

SM is initialised as:

Equation 12: $SMpd_0 = SMwppd + (PAWrootspd * k\_evapo_{mon})$

SMwppd is the soil water content at wilting point to the profile depth [section 2.1.1].

PAW600 is the plant available water to the profile depth (mm) [section 2.1.2].

k_evapo is a coefficient to account for the capability of soil to supply water for evaporation [section 2.2].

mon is the month the soil water calcuations start.

3.1.4. Soil water to rooting depth

The soil water content from the surface to the crop rooting depth (SMrd, mm) is used in the transpiration sub-model (section 3.4.1) and is calculated as shown in *Equation 13*. The rooting depth varies monthly as the crop grows and is harvested. Thus:

Equation 13: $SMrd_t = SMrd_{t-1} + DailyInput + DailyIrrigation - Wevapo - WTransp – ROsurface$

DailyInput is the daily rainfall and snow melt (mm/day) [section 3.1.5].

DailyIrrigation is daily irrigation (mm/day) [section 3.3.3].

Wevapo is the evaporation (mm/day) for crops [section 3.4.2].

WTransp is the transpiration (mm/day) for crops [section 3.4.1].

ROsurface is the surface runoff (mm/day) [section 3.5].

such that

Equation 14: $SMwp_{D,mon} < SMrd_t < SMwp_{D,mon} + CAW_{D, mon}$

CAW is the crop available water to the rooting depth D (cm) for a given month.

SMwp is the wilting point (mm) to the rooting depth D (cm) for a given month [section 2.1.1].

and where:

Equation 15: $SMwp_{D,\,mon} = SMwp_{Dprofile} * CAW_{D,mon} / PAW_{Dprofile}$

SMwp is the wilting point (mm) to the bottom of the profile, Dprofile [section 2.1.1].

CAW is the crop available water to the rooting depth D (cm) for a given month.

$PAW_{Dprofile}$is the available water holding capacity (mm) to the bottom of the profile [section 2.1.1].

The initialise soil water to the rooting depth at time 0 ($SMrd_0$) is estimated as shown in Equation 16.

Equation 16: $SMrd_0 = SMwp_{D,mon} + (SMpd_0 - SMwp_{Dprofile}) * CAW_{D,mon} / PAW_{Dprofile}$

SM is the soil water content to the bottom of the profile (mm).

SMwp is the wilting point (mm) to the bottom of the profile [section 2.1.1].

$SMpd_0$ is the soil water content to the bottom of the profile (mm) [Equation 12].

CAW is the crop available water to the rooting depth D (cm) for a given month.

$PAW_{Dprofile}$is the available water holding capacity (mm) to the bottom of the profile [section 2.1.1].

3.1.5. Drainage for the DCD sub-model

The DCD sub-model requires drainage at 300 mm. This is determined using the monthly crop SM model (Cichota *et al.*, 2012) run for 24 months, with the drainage from the last 12 months used in the DCD sub-model. It is assumed that all evaporation and transpiration comes from soil water within the top 300mm. Thus:

Equation 17: $SM_{mon} = SM_{mon-1} + RainIrr_{mon} - Transpiration_{mon} - Evaporation_{mon} - ROsurface_{mon} - drainage_{mon}$

SM_t is the soil water content (mm) to 300 mm on day t.

RainIrr is the sum of the daily rainfall and irrigation for the month (mm/month) [section 3.2].

Transpiration is the monthly tranpsiration (mm/month) [section 3.4.1].

Evaporation is the monthly evaporation (mm/month) [section 3.4.2].

ROsurface is the sum of the daily surface runoff for the month (mm/month) [section 3.5].

Drainage (mm/ month) as shown in Equation 19.

with SM constrained such that:

Equation 18: $SMwp300 < SM_{mon} < SMfc300$

Drainage is estimated as the greater of zero or:

Equation 19: $drainage_{mon} = SM_{t-1} + RainIrr - Transpiration_{mon} - Evaporation_{mon} - ROsurfacemon – SMfc$

SMfc is SM content at field capacity (mm) to 300 mm.

SM content at time 0 is estimated as:

Equation 20: $SM_0 = SMwp + (PAW_{30}) * k\_evapo_{12}$

AWC is the available water holding capacity (mm) to 300 mm [section 2.1.1].

k_evapo_{12} is k_evapo for Decemeber [section 2.2].

3.2. Daily inputs

3.2.1. Daily input

Daily inputs (mm/day) for estimating soil water contents are estimated as:

Equation 21: $DailyInput = dailyrainfall + snowmelt + dailyirrigation + diaryEffIrr$

dailyrainfall in daily rainfall (mm/day) [section 2.2].

snowmelt is the daily input from snowmelt (mm/day) [section 2.2].

dailyirrigation is the daily input from irrigation (mm/day) [section 3.3].

diaryEffIrr is the daily input from dairy effluent applications [section 3.3.4.1].

3.2.2. Effluent from dairy factories

Dairy factory effluent is typically low nutrient high volume (40,000 – 60,000 l/ha/application), and this means that sometimes there is sufficient water being applied to affect soil water contents. Therefore dairy factory effluent is included as an irrigation input. This also means that alternative methods of including dairy factory effluent such as added it as irrigation or as a fertiliser using litres or a nutrient loading have similar affects.

Thus when the rate (litres/month) of dairy factory effluent irrigation is entered, the irrigation rate (mm/month) is estimated as:

Equation 22: $DairyFactIrr = Effluentrate / 10000$

Effluentrate = application rate (litres/month)

and when a loading is entered, the irrigation rate is estimated as:

Equation 23: $DairyFactIrr = ((EffN / area_{block} / 0.0014/ 10000) + (EffK / area_{block} / 0.0015/ 10000)) / 2$

EffN is the loading of N (kg N/month).

EffK is the loading of K (kg K/month).

0.0014 is the average concerntationof N if dairy factory effluent.

0.0015 is the average concerntationof K if dairy factory effluent.

Dairy effluent is added when there are 3 days without rain. It is assume that if there is that much rain that this condition is not met then the impact from dairy effluent applications on soil water contents is negligible.

3.3. Irrigation

The daily rate of irrigation applied to the crop (section 3.3.3) is estimated from input data relevant to each irrigation scheduling strategy (2.3.3.2). The irrigation sub-model is integrated with the rest of the soil water sub-model (section 3.1). The amount of irrigation applied is based on soil moisture in the top 600 mm of the soil. The amount of pumped water is also estimated, this being the rate of irrigation applied to the crop plus additional losses (section 3.3.4) other than those linked directly to the soil water calculations.

These estimations may also require estimation of the deficit (section 3.3.1) and time since irrigation (section 3.3.2). Irrigation depth is estimated (3.3.3.1) using the selected irrigation scheduling options described in section 2.3.3, or from frost protection inputs (section 3.3.3.2) or a monthly application depth (3.3.3.3). Additional water losses due to the delivery system (3.3.4.1), additional atmospheric losses (3.3.4.2), or outwash (3.3.4.3) are also estimated.

3.3.1. Deficit

The soil water deficit is

Equation 24: Deficit = SMfc600 – SM600

SMfc600 is the soil water content at field capacity (mm) to 600 mm [2.1.1].
SM600 is the soil water content (mm) to 600 mm [3.1.1].

3.3.2. Time since irrigation

The time since irrigation was applied (number of days) is used to determine whether sufficient time has lapsed to trigger an irrigation event based on the return period. The time since irrigation is applied is estimated as:

- If irrigation is applied on a given day then time since irrigation was applied is set to 1, otherwise time since irrigation was applied is incremented by one.
- If no irrigation is applied during the month, time since irrigation is set to zero.
- If irrigation has not been applied in the previous month (time since irrigation is zero) and is applied in the current month, then time since irrigation is set to the default or entered return period or the minimum return period if return period is not a required input. Thus, the first irrigation once a sequence of irrigations occur is on the first of the month. Otherwise time since irrigation is set to 1.

For pastoral, cut and carry and fruit crop blocks, as noted in section 3.1, the daily soil water contents are estimated for two years, starting on January 1. The start date cuts across the typical irrigation season and hence time since irrigation is initialised on day 0 to take account of any timing carry over from the previous month. Thus, time since irrigation is initialised to zero unless irrigation is applied in the previous and current month (that is, December and January), then time since irrigation is initialised as:

- If the return period is greater than the number of days in December, then time since irrigation is set to the return period.
- Otherwise, if days in December less the return period is greater than the return period, then

  Equation 25: $\text{timesinceIrrigation} = \text{DaysInMonth}_{\text{Dec}} - \text{ReturnPeriod} * \text{Ncycles}$

  where

  Equation 26: $\text{Ncycles} = \text{Integer}(\text{DaysInMonth}_{\text{Dec}} / \text{ReturnPeriod})$
- otherwise

  Equation 27: $\text{timesinceIrrigation} = \text{DaysInMonth}_{\text{Dec}} - \text{ReturnPeriod}$

Thus if there is a return period of 10 days, irrigation is applied on the 1st, 10th, 21st, etc. in the first month irrigation is applied. If the return period is 14 days, then irrigation is applied on the 1st, 14th, 28th, etc. This can lead to three irrigation events in the first month and only two in subsequent months.

For crop blocks, time since irrigation is initialised as zero. Hence if the crop ends in December, and irrigation is applied in the first month (January), then the first irrigation event is on the first of the month.

3.3.3. Irrigation applied

3.3.3.1. *Irrigation scheduling options*

The management options define the depth per application and frequency of application, and whether these are fixed or vary with soil water content. Each day, the estimated irrigation depth is zero unless an irrigation event is triggered.

For the following conditions:

- controlled flood and border dyke irrigation systems, or
- irrigation scheduling is based on ‘Fixed depth and return period’ or ‘Visual assessment/dig a hole’

then if time since irrigation equals or is greater than the entered or default return period then an irrigation event is triggered, and the irrigation depth applied to the crop or pasture (mm/day) is estimated as:

Equation 28: $\text{dailyirrigation} = \text{Specifieddepth}$

Specifieddepth is the entered of default depth of application (mm/application).

If the strategy selected is 'Trigger point; fixed depth applied', then an irrigation event is triggered when:

Equation 29: $\text{deficit} > \text{PAW}_{60} * (1 - \text{TriggerPoint}/100))$ units = 1

$\text{deficit} > \text{TriggerPoint}$ units = 2

PAW_{60} is the profile available water to 600 mm (mm) [section 2.1.2].

TriggerPoint is the entered trigger soil water level to start applying irrigation, as % of PAW (unit = 1) or mm deficit (unit =2).

deficit (mm) is the soil water deficit (mm) [section 3.3.1].

and if a minimum return period is entered or default management definition option is selected, then the time since irrigation is equal to or greater than the minimum return period. If an irrigation event is triggered, then the application depth is estimated as in Equation 28.

If the strategy selected is 'Depth applied to achieve target; fixed return period' an irrigation event is triggered when the time since irrigation is equal to the return period: The application depth is estimated as:

Equation 30: $\text{dailyirrigation} = \text{deficit} - (\text{PAW}_{60} * (1 - \text{TargetPoint}/100))$ units = 1

$= \text{deficit} - \text{TargetPoint}$ units = 2

PAW_{60} is the profile available water to 600 mm (mm) [section 2.1.2].

TargetPoint is the entered target soil water level to irrigation to, either as % of PAW (unit = 1) or mm deficit (unit =2).

deficit (mm) is the soil water deficit (mm) [section 3.3.1].

The application depth is constrained by minimum application depth (if entered or default option is selected) and the maximum application depth (if entered or default option is selected), that is:

Minimum depth ≤ dailyirrigation ≤ maximum application depth

If the strategy selected is 'Depth applied to achieve target; fixed return period, then an Irrigation event is triggered as in Equation 29, and the application depth is estimated as in Equation 30. There is no need for constraints on the application depth or minimum return periods.

3.3.3.2. *Frost protection*

Many orchardists apply water as a frost protection measure. The irrigation management rules do not apply as the water is not being applied to overcome a soil water deficit. Therefore, the amount of water applied for frost protection can be estimated based on typical frost characteristics, or a specific depth can be added for each month.

As the daily timing cannot be determined, it is assumed that water is applied evenly throughout the month. The daily depth of irrigation applied for frost protection is estimated as:

Equation 31: $\text{dailyirrigation} = \text{FrostIrrigation}_{\text{mon}} / \text{DaysinMonth}_{\text{mon}}$

FrostIrrigation is the calculated amount of water added for frost protect (mm/month) [Equation 32].

DaysinMonth is the number of days in a month.

The calculated amount of irrigation applied in a month is estimated as:

Equation 32: $\text{FrostIrrigationmon} = \text{FrostDegree} * \text{FrostHours} * \text{FrostDays} * 3$

FrostDegree is the average frost (°C) on days that frost occur for the given month. Frost is defined as the °C below zero.

FrostHours is the average duration of the frost in a given month (hours) on days that frost occur for the given month..

FrostDays is the number of days of frost. In the that occur in a given month.

3 is the irrigation rate (mm/hr/°C).

3.3.3.3. *Application depth*

The application depth is a monthly rate of water added. If an application depth is entered, the timing of individual irrigation events cannot be estimated. Thus, it is assumed that water is applied evenly throughout the month.

This option is least preferred as the irrigation application depth should be aligned with the climate data and the irrigation management practices used. This is difficult to achieve. However, it may be useful for some situations, where a fixed amount of water is applied for a given month.

Equation 33: $\text{dailyirrigation} = \text{ApplicationDepth}_{\text{mon}} / \text{DaysinMonth}_{\text{mon}}$

ApplicationDepth is the entered application depth (mm/month).

DaysinMonth is the number of days in a month.

If the method of application is border dyke, then outwasjh loss is assumed to be zero.

3.3.4. Additional water losses

The primary losses of water due to irrigation is encapsulated in the estimation of daily soil water (section 3.1). Irrigation water applied to the pasture or crop (section 3.3.3) is added to soil water, and hence can affect water movement such as evapotranspiration (section 3.4), surface runoff (section 3.5), and drainage (section 3.6).

The irrigation sub-model also includes four additional water losses:

- Delivery system losses caused by leakages from the irrigation equipment.
- Atmospheric losses which represent additional water lost as evaporation before the water reaches the soil surface and/or as aerial spray drift.
- Border dyke outwash.
- Additional losses because of non-uniformity of water application.

These losses are included in water that is pumped (sent to the block or farm) but effectively do not contribute to the block soil water contents (section 3.1). However, these additional losses can include nutrients that are lost from the block or farm.

3.3.4.1. *Delivery system losses*

Delivery system losses are losses from the delivery system, including from leaking pipes, connections, and taps, or water races, etc.

Equation 34: $\text{DeliveryDrainageLoss} = \text{dailyirrigation} * \text{DrainageLoss} / 100$

Dailyirrigation is the estimated daily irrigation applied (mm/day) [section 3.3.3].

Drainage loss is the estimated losses (%) [Table 10].

Table 10. Delivery system losses for each irrigation system type.

Irrigation system type	Condition	Delivery system losses (%)
Linear and centre pivot	PAW < 75mm	3
	PAW ≥75mm	2
Travelling irrigator	none	3
Spraylines	none	3
Micro-irrigation (drip and sprinkler)	none	3
Solid set	none	3
Controlled flood	none	5
Border dyke	none	5

The loss factors are based on industry experience gained across a number of modelling studies (J Bright, Aqualinc, pers comm.).

3.3.4.2. *Additional atmospheric losses*

Water lost directly to the atmospheric, including atmosphere typically as aerial spray drift, is estimated as:

Equation 35: AdditionalAtmosLoss = dailyirrigation * AtmosLoss / 100

Dailyirrigation is the estimated daily irrigation applied (mm/day) [section 3.3.3].

AtmosLoss is the estimated loss to atmosphere (%) [Table 11].

This loss is in addition to that lost by evapotranspiration (section 3.4) to the atmosphere, which can be higher under irrigation due to higher soil water contents.

Table 11. Additional atmospheric losses when applying irrigation.

irrigation system type	Condition	Atmospheric losses (%)
Linear and centre pivot	PAW < 75mm	3
	PAW ≥ 75mm	3
Travelling irrigator	none	2
Spraylines	none	2
Micro-irrigation (drip and sprinkler)	none	2
Solid set	none	2
Controlled flood	none	0
Border dyke	none	0

The loss factors are based on industry experience gained across a number of modelling studies (J Bright, Aqualinc, pers. comm.).

3.3.4.3. *Controlled flood and border dyke outwash*

In border dyke systems, a proportion of the applied irrigation can drain from the end of the border as outwash. McDowell and Rowley (2008) reported results that indicate outwash ranged from 25-32% of applied irrigation in two studies. They used a typical value of 25%. Monaghan *et al*. (2009) reported losses that averaged 50% on a heavy soil. Based on experience, Monaghan (pers. comm.) suggested that:

> *"poor management on heavy soils can lead to outwash of about half of what is applied whereas with good management on light soils, losses should be less than 10% of applied. Most irrigators aim for less than 10%, but often don't achieve this for various management reasons."*

Since these studies were published, there has been an effort to reduce irrigation outwash. Therefore, on systems where outwash occurs, outwash is assumed to be 16% of applied irrigation. On systems where outwash from the border dykes is minimal or does not occur, outwash is set to zero.

There are now systems where the outwash is minimal or does not occur. In the 'No outwash' option is selected, then estimated outwash is zero.

With controlled flood irrigation, the outwash is essentially uncontrolled and probably makes its way to either streams and rivers or remains somewhere within the landscape. Given the later can occur, it was assumed that outwash loss rate was half that from border dyke.

The application of outwash water to another block has no effect on the hydrology sub-model as the water applied is entered as for any other irrigation system. Nutrient concentrations in the irrigation water should reflect that the source is outwash water.

3.3.4.4. *Non-uniformity losses*

Inefficiencies related to the way irrigation water is applied are likely. For example, overlap or, uneven (non-uniform) distribution may lead to uneven application of water and the subsequent drainage. Border-dyke irrigation results in uneven application across a paddock because excess water is supplied at the top of the paddocks to ensure that some water will reach the bottom of the paddocks. This can lead to drainage occurring at the top of the paddock even though no drainage would occur if the same volume of water were distributed evenly across the paddock. The non-uniform application by other systems can also lead to parts of a block receiving more or less water than the average amount of water. Currently, it is assumed that water is applied evenly across the block. However this means that drainage, and probably N leaching may be underestimated if applications are not uniform, and that any effects from improving uniformity, for example from the use of short booms or variable rate applicators, are not captured.

The arrangement of irrigation systems on blocks can also lead to can also lead to different coverage of blocks, or inefficiencies on a block basis. For example, on square blocks with centre pivots, the corners are often either un-irrigated, or other delivery systems such as set spray systems in the corners would provide higher coverage than centre pivot alone. These effects are assumed to be relatively small, or can be modelled as separate blocks.

3.4. Actual evapotranspiration

Actual evapotranspiration (AET, mm/day) comprises both evaporation and transpiration components, that is:

Equation 36: AET = Transpiration + Evaporation

Transpiration is the daily evaporation from the soil (mm/day) [section 3.4.1].

Evaporation is the daily evaporation from the soil (mm/day) [section 3.4.2].

If removing AET results in soil water content to 600 decreasing below wilting point to 600mm, that is SM600 - AET < SMwp600, then evaporation and transpiration is set to zero

PET is allocated between evaporation and transpiration by cover, which is defined as the proportion of ground covered by leaves. Hence, a cover of zero implies bare ground, while a cover of one implies full canopy cover. Both evaporation and transpiration decline under dry conditions to give AET.

On pastoral and cut and carry blocks, it is assumed that pastoral cover is close to one most of time and hence evaporation is negligible. On crop blocks, cover varies with stage of growth while on fruit crop blocks, cover varies with season as outline in the Crop section of the Technical manual.

3.4.1. Transpiration

Transpiration (mm/day) is estimated each day as:

Equation 37: Transpiration = PET * Cover * fTransReduct

PET is Potential Evapotranspiration (mm/day) [section 2.2].

Cover is the monthly crop cover (0-1).

fTransReduct is the factor for reduction in transpiration due to dryness [see below].

If PET is greater than the difference between soil water content and soil water content at wilting point, then the factor for determining the reduction in transpiration due to dryness (fTransReduct) is estimated as:

Equation 38:
$$\text{fTransReduct} = \begin{cases} 1 & (\text{SMrd} - \text{SMwp}_{D,mon}) > \text{SMcritical} \\ (\text{SMrd} - \text{SMwp}_{D,mon}) / \text{SMcritical} & \text{otherwise} \end{cases}$$

SMrd is the soil water content (mm) on day t to crop rooting depth [section 3.1].

$\text{SMwp}_{D,mon}$ is the wilting point (mm) to the crop rooting depth, D, for a given month [section 2.1.1].

SMcritical is the soil water content that PET starts to decrease (mm).

Otherwise, if the soil water content is greater than PET, or if difference between soil water content and soil water content at wilting point is greater than the soil water content that PET starts to decrease (SMcritical), then fTransReduct is one (i.e., there is no reduction).

Reported soil water contents at which AET starts to decrease below PET in pastoral systems (AET/PET is less than 1) have been reported to be 0.34 maximum soil water deficit (Parfit *et al*., 1985a), 0.41 (Parfit *et al*., 1985b), 0.65 (McAneny and Judd, 1983, see McAneny *et al*., 1982), or 0.50 (Martin, 1990) of available water capacity.

Thus, the critical SM (mm) is estimated as:

Equation 39: $SMcritical_{mon} = CAW_{D,\,mon} * 0.5$

$CAWwp_{D,mon}$ is the crop available water (mm) to the crop rooting depth, D, for a given month [section 2.1.1].

For crops, $CAWwp_{D,mon}$ varies each month and hence SMcritical varies. For pastoral blocks, $CAWwp_{D,mon}$ is constant and to 600 mm or the maximum rooting depth (section 2.1.2) for non-lucerne pasture, and 1500mm for lucurne.

This differs from the method in Rutherford *et al*. (2008) who used a value of 0.65 SMfc for SMcritical in pastoral systems. The crop sub-model differs from that published in Cichota *et al*. (2012) as they used a monthly-based model whereas this one is a daily model.

3.4.2. Evaporation

Evaporation (mm/day) is initially estimated each day as:

Equation 40: $Evaporation = PET * (1 - Cover)$

PET is Potential Evapotranspiration (mm/day) [section 2.1.1].

Cover is the monthly crop cover (0-1).

Note that evapotranspiration is reduced on wet days (daily inputs are greater than zero) as described in the Climate Technical Manual section.

The effect of soil dryness on evaporation is modelled by assuming that the maximum rate of evaporation is the estimated difference between soil water content in the top 100 mm of soil (section 3.1.2), and soil water content at wilting point. However, a minimum evaporation rate is 10% of the initial estimated rate is assumed, that is, some water is available from the lower profile, for example as capillary rise.

3.5. Daily surface runoff

Surface runoff (mm/day) is the difference between daily inputs and the threshold required to produce infiltration-excess surface runoff (mm/day). Thus, when daily inputs exceed surface threshold, surface runoff (mm) is estimated as:

Equation 41: $ROsurf = dailyrain - SurfaceThreshold$

Dailyrain is daily inputs of rainfall and irrigation (mm/day) [section 3.1.5].

$SurfaceThreshold_{day}$ is the daily rainfall at which surface runoff starts [section 3.5.1].

Generally, flat blocks produce no infiltration-excess surface runoff unless ponding (section 3.5.6) occurs, while steep slopes generate more surface runoff.

3.5.1. Surface threshold

Surface threshold (mm) is the daily rainfall at which surface runoff starts. The processes that determine the surface threshold are understood, but it is not possible to estimate surface threshold precisely for a particular property from the easily available soils, slope and vegetation data. The value of surface threshold depends on soil permeability, being higher on sandy soils than on clays. Thus, it was assumed that clay content was a useful predictor of soil permeability (Rutherford 2008). Soil water content affects the infiltration rate of the soil. Some soils are hydrophobic when dry and repel water, that is, surface threshold is low in summer when soil water content is low. This may lead to infiltration-excess surface flow in summer at lower rainfall rates than in autumn, winter and spring although in summer soil cracking and macropore flow may allow surface flow to re-infiltrate and thereby offset the effects of hydrophobicity. In winter when soil water content is close to field capacity, surface runoff is likely at lower rainfall rates than when the soil is drier. Steep soils are more likely to generate surface flow than flat soils (viz., surface threshold is lower on steep than flat land). If mole/tile drains are present, the likelihood of surface flow is significantly reduced (viz., surface threshold is increased).

Conceptually, surface threshold is determined as the amount of daily input required to produce infiltration-excess surface runoff and is estimated as a reference daily rainfall that generates surface runoff (Ksoil) multiplied by factors for slope, soil water content, hydrophobicity, and drainage systems. Thus, conceptually, surface threshold (ST):

Equation 42: $ST_{day} = Ksoil * Fslope * Fmoist * Fhyd * Fdrain$

Ksoil is the reference rainfall that generates surface runoff [section 3.5.2].

Fslope = 3, 1, 0.75, 0.5 for flat, rolling, easy hill and steep hill topography.

Fdrain is the drainage factor (0-1) [section 3.5.5].

Fmoist and Fhyd are factors for daily soil water content and hydrophobicity.

Testing of the scaling factors Fmoist and Fhyd show that surface threshold can drop below the values expected at moderate soil water. To avoid this problem, the scaling factors were expressed as ratios calculated using SM content, and reference soil water. Thus:

Equation 43: $ST_{day} = Ksoil * Fslope * Fdrain * Fmoist_{SM}/Fmoist_{SMref} * Fhyd_{SM}/Fhyd_{SMref}$

Ksoil, Fslope and Fdrain are defined in Equation 42.

$Fmoist_{SMref}$ and $Fmoist_{SM}$ is the soil moisture factor (0-1) calculated using SM_{ref} and SM from the previous day respectively [section 3.5.3].

$Fhyd_{SMref}$ and $Fhyd_{SM}$ is the hydrophobicity factor (0-1) calculated using SM_{ref} and SM from the previous day respectively [section 3.5.4].

Only the scaling factors $Fmoist_{SM}$ and $Fhyd_{SM}$ are dependent on daily values. Hence, surface threshold was calculated as:

Equation 44: $SurfaceThreshold_{day} = BaseInfilRate * Fmoist_{day} * Fhyd_{day}$

Fmoist is the soil moisture (0-1) calculated using SM [section 3.5.2].

Fhyd is the hydrophobicity factor (0-1) calculated using SM [section 3.5.4].

SM is soil water content (mm) from the previous day.

BaseInfilRate can be calculated as:

Equation 45: $\text{BaseInfilRate} = \text{Ksoil} * \text{Fslope} * \text{Fdrain} * 1/\ \text{Fmoist}_{\text{SMref}} * 1/\ \text{Fhyd}_{\text{SMref}}$

Ksoil, Fslope and Fdrain are defined in Equation 42.

Fmoist is the soil moisture factor (0-1) calculated using SM_{ref} [section 3.5.3].

Fhyd is the hydrophobicity factor (0-1) calculated using SM_{ref} [section 3.5.4].

where

Equation 46: $\text{SM}_{\text{ref}} = 0.75 * \text{SMfc600}$

SMfc600 is soil water content (mm) at field capacity to 600 mm [section 2.1.1].

Rutherford *et al*. (2008) did not separate rolling and easy hill, so easy hill was estimated as the mean between rolling and steep hill country.

Surface threshold is reduced by 20% if the occurrence of pugging occurrence class is greater than three and the months are May, June, July or August, or if the occurrence of pugging occurrence class is 4 (see Characteristics of Soils chapter of the Technical Manual for definition of pugging occurrence class).

3.5.2. Reference daily rainfall that generates surface runoff

Ksoil is the reference daily rainfall that generates surface runoff, which is related to clay content. The value depends on soil permeability, which is related to soil clay content (Figure 3). Where hydrophobicity is not a factor, infiltration rates will be higher when the soils are dry due to higher sorptivity and/or summer cracking.

Equation 47: $\text{Ksoil} = (90.54 * \exp(-0.0267 * \text{Topclay}))$

Topclay is the top soil clay content (%).

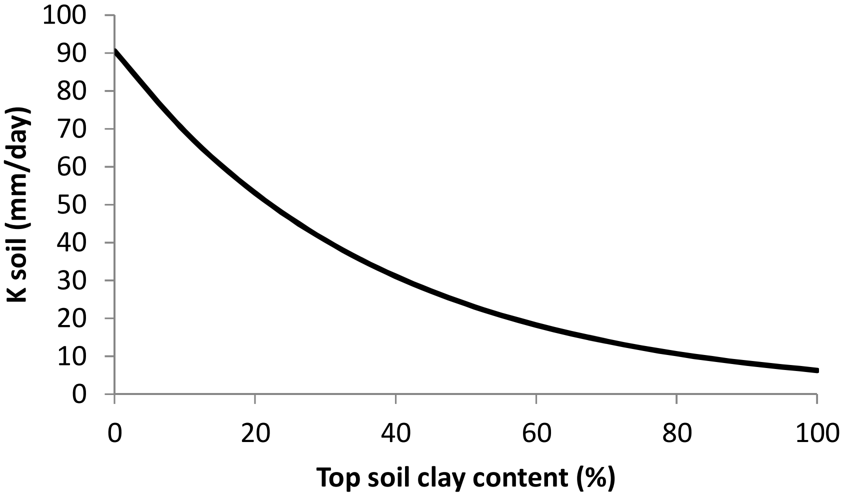

Figure 3 Relationship between top soil clay content (%) and reference daily rainfall that generates surface runoff (Ksoil).

3.5.3. Soil moisture factor

If all other factors are constant, it was assumed that runoff increases as soil water content decreases. The soil moisture factor is estimated as:

Equation 48: $$\text{Fmoist} = (1 + (\text{alpha} * \text{SMfc} - \text{SM}) / (\text{beta} * \text{SMfc} + \text{abs}(\text{alpha} * \text{SMfc} - \text{SM}))) / 2$$

SMfc is the soil water content at field capacity (mm) to 600mm depth.
SM is either the reference SM or SM content on a given day (mm).

The coefficients alpha (1) and beta (0.5) determine the soil moisture above which rainfall required to cause surface flow declines from the reference value. Note that these coefficients apply for the modelled method of estimating surface threshold. The relationship between Fmoist and soil water content (expressed as a ratio of field capacity) is shown in Figure 4.

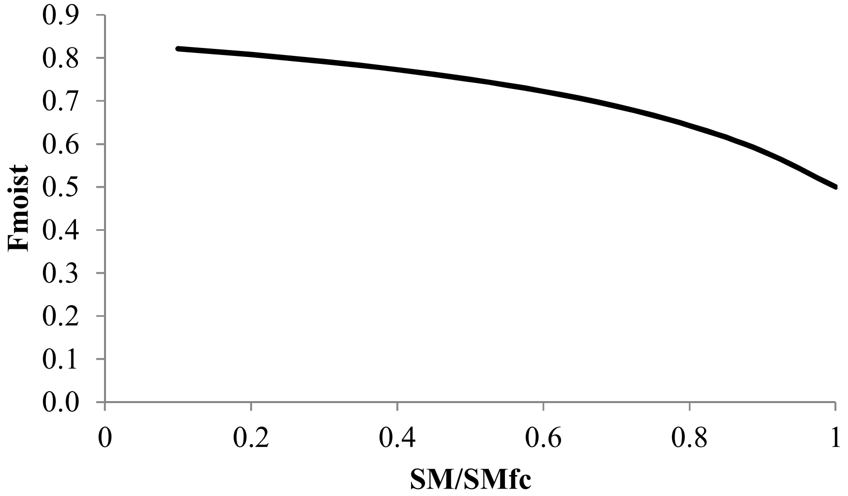

Figure 4. Relationship between SM/SMfc and Fmoist.

3.5.4. Hydrophobicity factor

The effect of hydrophobicity, or water repellency on the surface of the soil, of daily surface runoff is estimated as:

Equation 49: Fhyd = SM / (gamma * SMfc + SM)

SM is either the reference SM or SM content on a given day (mm).

SMfc is the soil water content at field capacity (mm) to 600mm depth.

gamma = 0.0484, 0.2644, 0.6077 for the options Never, Occasionally, and Frequently respectively. Never is the default.

Gamma determines the soil water content below which the soils become hydrophobic. The relationship between Fhyd and soil water content (expressed as a ratio of field capacity) is shown is Figure 5.

The value of gamma can be estimated if values are known for the rainfall that generates surface runoff when the soil is wet K_{wet} and when it is dry K_{dry}. K_{wet} occurs when SM = δ SMfc and K_{dry} when $SM = \sigma$ SMfc where $\delta \sim 0.9$ and $\sigma \sim 0.1$ are non-dimensional scaling factors. The values of gamma correspond to ratio of Kwet/Kdry of 1, 2 and 3.

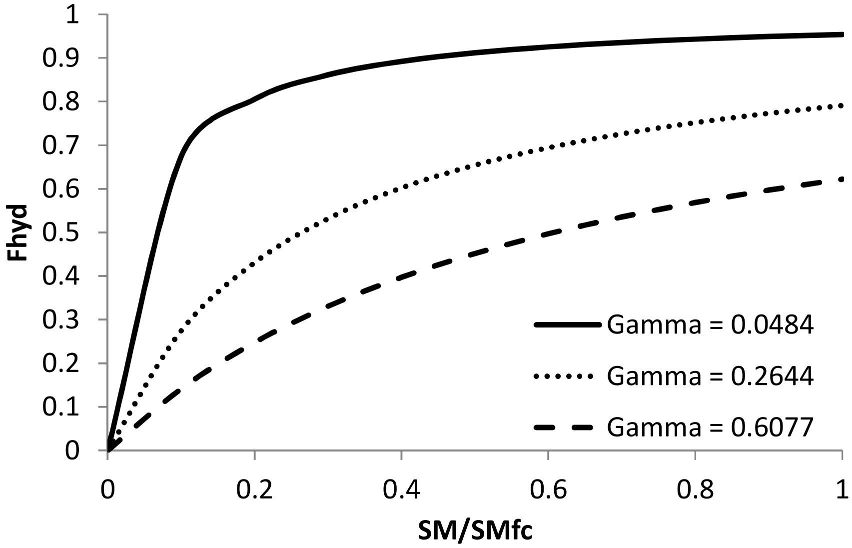

Figure 5. Relationship between SM/SMfc and Fhyd at three gamma values.

3.5.5. Drainage factor

Added drainage is assumed to increase the infiltration rate as defined by the factor Fdrain. Fdrain does not distinguish between drainage methods.

Equation 50: Fdrain = 1 propdrained = 0
= 4 * propdrained otherwise
propdrained is the proportion of a paddock's drainage that ends up in drains (0-1) [section 5.3].

3.5.6. Ponding

To prevent SM levels increasing above saturation, runoff was increased once saturation occurred. This would represent ponding. Soil water contents were initially calculated as in section 3.1.1, and then is soil water content was 10% greater than soil water at saturation, that is:

Equation 51: (SM600 – ROdrain600) > (1.1 * SMmax600)

and daily surface runoff adjusted to:

Equation 52: ROsurface = ROsurface + (SM600 – ROdrain600) - (1.1 * SMmax600)
SM600 is the soil water content (mm) on day t-1 [Equation 5].
ROsurface600 is the surface runoff (mm/day) [section 3.5].
ROdrain600 is the drainage from root zone (mm/day) [section 3.6]

3.6. Daily drainage below root zone

Drainage occurs when soil water content exceeds field capacity. The fastest drainage rate is determined by Ksat, and the soil water content that this occurs is SMmaxd, defined as:

Equation 53: SMmaxd = 0.75 * (SMsat600 – SMfc600)

SMfc600 is the soil water content at field capacity (mm) to 600 mm [section 2.1.1].

SMwp600 is the soil water content at wilting point (mm) to 600 mm [section 2.1.1].

If SM is greater than SMmaxd at the start of the day then drainage equals Ksat for the period deltaT and then decreases linearly with SM, where deltaT is estimated as:

Equation 54: deltaT = (SM600$_{t-1}$ – Smmaxd600) / Ksat   SM600 > SMmaxd
= 0   otherwise

SM600 is the soil moisture on day t-1 (mm) to 600 mm [section 3.1.1].

SMmaxd is as in Equation 53.

Ksat is the saturated hydraulic conductivity (mm/day) [section 2.1.3].

Note that the saturated hydraulic conductivity in the Characteristics of Soils chapter of the Technical Manual section has units of m/day, and hence is multiplied by 1000. Thus, daily drainage below 600 mm (mm/day) is estimated as:

Equation 55: ROdrain600$_t$ = 0   SM <= SMfc
= (SM600$_{t-1}$ – SMfc600) * (1 - exp(-Ksat/(SMmaxd – SMfc600)))   deltaT = 0
= Ksat * deltaT + SMdiff   0 < deltaT < 1
= Ksat   deltaT ≥ 1

SM600 is the soil water content (mm) on day t-1 [section 3.1].

SMfc600 is the soil water content at field capacity (mm) to 600 mm [section 2.1.1].

SMmaxd is as in Equation 53.

deltaT is as in Equation 54.

Ksat is the saturated hydraulic conductivity (mm/day) [section 2.1.3].

and where

Equation 56: SMdiff = (SMmaxd – SMfc600) * (1 - exp(-Ksat*(1-deltaT)/(SMmaxd – SMfc600)))

SMmaxd is as in Equation 53.

SMfc600 is the soil water content at field capacity (mm) to 600 mm [section 2.1.1].

deltaT is as in Equation 54.

Ksat is the saturated hydraulic conductivity (mm/day) [section 2.1.3].

A similar procedure is undertaken for estimating drainage below the profile depth but substituting in the appropriate data to give ROdrainpd$_t$.

3.7. Outputs

3.7.1. Average monthly soil moisture contents

The OVERSEER engine requires average monthly soil moisture values (mm). These are estimated as:

Equation 57: $\text{WSoilMoistMon600}_{\text{mon}} = \sum(\text{SM600}_t) / \text{DaysInMonth}_{\text{mon}}$

SM600 is the soil water content (mm) to 600 mm for each day in month mon [3.1.1].

3.7.2. Summation outputs

Daily calculated values are summed to monthly totals. The monthly summation variable, daily variable that is summed and the section the daily variable is calculated is shown in Table 12.

Table 12. Monthly variables, daily variable summed to give monthly variable.

Monthly variable	Daily variable	Section
WIrrigAppMon	dailyirrigation	3.3.3
WDrainageMon600	ROdrn600	3.6
WRunoffMon	ROsurf600	3.5
WTranspirMon	Transpiration	3.4.1
WEvapoMon	Evaporation	3.4.2
WDrainageMon	ROdrnpd	3.6
MonExtraDrainage	DeliveryDrainageLoss	3.3.4.1
MonExtraAtmos	AdditionalAtmosLoss	3.3.4.2
MonOutwashLoss	OutwashLoss	3.3.4.3

The monthly outputs are also summed up to an annual total for reporting or modelling purposes.

Delivery system losses (section 3.3.4.3) are added to total block drainage at reporting time. They are not included in WDrainageMon600 or the yearly summation, both of which are typically used in the rest of the OVERSEER Engine when a drainage value is required.

3.7.3. Irrigation supplied

The irrigation sub-model in section 3.3.3 estimates the amount of irrigation water applied to the soil. The irrigation water supplied to the block is estimated as:

Equation 58: $\text{IrrSupplied} = \sum(\text{WIrrigAppMon}_{\text{mon}} + \text{MonOutwashLoss}_{\text{mon}} + \text{MonExtraDrainage}_{\text{mon}} + \text{MonExtraAtmos}_{\text{mon}})$

WIrrigAppMon is the depth of irrigation water applied (mm/year) [section 3.3.4.3].

MonOutwashLoss is the depth of outwash loss (mm/month) [section 3.3.4.3].

$\text{MonExtraDrainage}_{\text{mon}}$ is the depth of additional drainage associated with delivery system losses (mm/month) [section 3.3.4.3].

MonExtraAtmos is the depth of additional atmospheric losses (mm/month) [section 3.3.4.3].

3.7.4. Output checks

To ensure that the outputs balance for reporting purposes, water inputs and outputs are balanced by adjusting AET. A small discrepancy can occur due to soil moisture content at the beginning and end of year being slightly different. This is more likely to occur on crops where the crop water use may vary between years depending on the crop management entered. The method also means that additional atmospheric losses (section 3.3.4.2) are incorporated into the annual AET estimate. Thus:

Equation 59: $AET_{annuatl} = Rainin + \sum_{mon}(WIrrigAppMon + RainFromSnow)) - (\sum_{mon}(WDrainageMon600 + WRunoffMon + MonOutwashLoss))$

Rainin is the entered annual average rainfall (mm/year).

WIrrigAppMon is the total monthly irigation depth (mm/month) [section 3.7.2].

RainFromSnow is snowmelt (mm/month) [section 2.2].

WDrainageMon600 is monthly total drainage at 600 mm depth (mm/month) [section 3.7.2].

WRunoffMon is the monthly runoff (mm/month) [section 3.7.2].

MonOutwashLoss is the depth of outwash loss (mm/month) [section 3.7.2].

If annual AET is less than zero, then monthly drainage is adjusted as shown in Equation 60.

Equation 60: $Drainage_{mon} = Drainage_{mon} * (Drainage_{year} + AET_{year}) / Drainage_{year}$

4. Shallow ground water

The shallow ground water was based on that reported by Rutherford *et al.* (2008). Daily total runoff below the root zone predicted by the Porteous model must be separated into its various components: (a) surface flow that passes through wetlands and filter strips, (b) re-emerging shallow groundwater that passes through wetlands and/or drainage systems, and (c) deep drainage that does not reappear on the property.

The difference between total and surface runoff enters the ground before re-emerging after delays of minutes-decades. Daily total runoff minus daily surface runoff is routed using a simple groundwater model to predict shallow sub-surface runoff and saturation-excess overland flow (if any). This is then added to infiltration-excess overland flow to give the total surface flow that re-emerges on the property and may enter a wetland, contour or riparian filter strip.

A simple reservoir aquifer sub-model is used to estimate sub-surface runoff to the riparian zone along the edge of stream channels and to wetlands. The hill slope is conceptualised as shown in Figure 6. We assume that:

- drainage ROrootdrain (mm/d) is steady and spatially uniform

- there is an aquitard at depth Hsoil (m)
- a proportion of drainage (1-ϕ) flows to deep groundwater through the aquitard
- the remaining proportion of drainage re-emerges on the property after some delay
- the average hill slope length is Lslope (m)
- hill slopes on both banks drain to streams
- the length of stream channel is Lwet (m)
- groundwater flow is governed by Darcy's Law
- water level in the aquifer (H) varies with time
- when water level in the aquifer (H) is greater than the aquitard at depth(Hsoil), saturated flow occurs, and
- the length of the saturated zone is Lsat (m).

Each day, aquifer volume is adjusted for drainage in and out, and the height of water and length of the saturation zone calculated.

Shallow ground water is only required for the wetland sub-model. Hence, the proportion of re-emergent flow and aquitard depth are linked to the wetland inputs. For the wetland sub-model, the conduit carrying water to the wetland has two banks with an aquifer on each side. This is shown in the Wetland section of the technical manual.

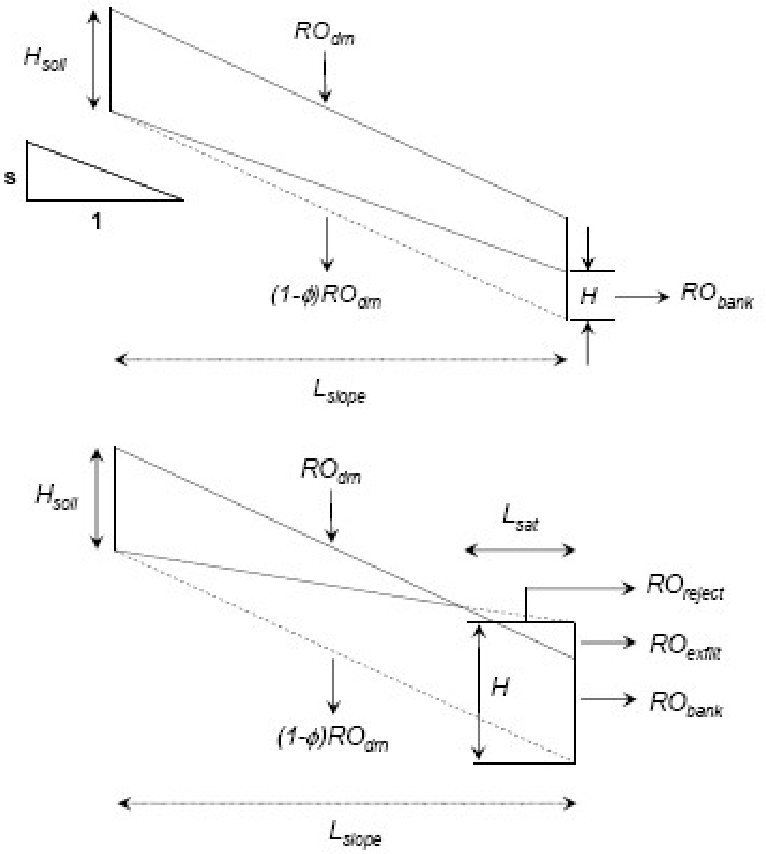

Figure 6. Conceptual model for sub-surface drainage from a hill slope into a riparian zone when the aquifer is partially filled, and over filled. Note that hill slopes occur on both sides of most streams. Taken from Rutherford *et al.* (2008)

The ground water model does not operate on block scale as the daily soil water model does. Rather it operates on a catchment scale (catchment of the riparian strip or wetlands), with more than one block, or areas outside the farm, contributing to the catchment. Therefore, any block inputs required for the model are weighted according to the area and proportion of block contributing to the catchment.

4.1. Aquifer characteristics

The wetland sub-model assumes that the wetland has two hill slopes, and that there is an aquifer on each side of the wetland.

4.1.1. Aquifer volume

The aquifer volume (m^3) can be estimated each day as:

Equation 61: $AqVol_t = AqVol_{t-1} - Qbank - Qexfil - Qreject - Qdeep + Qdrainageinput$

Qbank is the seepage flow from the aquifer (m^3/day) [section 4.2.4].

Qexfil is flow (m^3/day) from the saturation part of the aquifer [section 4.2.5].

Qreject is the flow (m^3/day) rejected from the aquifer when the aquifer is saturated [section 4.2.6].
Qdeep is flow (m^3/day) to deep aquifers [section 4.2.2].
Qdrainageinput is the flow (m^3/day) from drainage from the root zone [section 4.2.1].

As the volume of deep drainage is not used in the wetland sub-model, and combining reject flow with drainage input, the aquifer volume (AqVol, m^3) is estimated each day as:

Equation 62: $\text{AqVol}_t = \text{AqVol}_{t-1} - \text{Qbank} - \text{Qexfil} + \text{Qnetinput}$
Qbank is the seepage flow from the aquifer (m^3/day) [section 4.2.4].
Qexfil is flow (m^3/day) from the saturation part of the aquifer [section 4.2.5].

and where

Equation 63: Qnetinput = phi * WtROrootdrain / 1000* (Lslope - Lsat) * Lwet
phi is the proportion of re-emergent flow [section 4.1.9].
WtROrootdrain (mm/day) is the block weighted average drainage input [section 4.2.2].
Lsope is the length of slope (m) [section 4.1.7].
Lsat is the length of saturated zone (m) [section 4.1.8].
Lwet is the length of wetland (m) [section 4.1.6].

At time 0, the aquifer volume (m^3) is estimated as:

Equation 64: AqVol = Hsoil * Lwet * (Lslope + Lsat) / 2 if Hres > Hsoil
= Hres * Lslope * Lwet / 2 otherwise
Hsoil is the aquitard depth (m) [section 4.1.3].
Hres is the aquifer water height (m) [section 4.1.5].
Lwet is the length of wetland cathment (m) [section 4.1.6].
Lsope is the length of slope (m) [section 4.1.7].
Lsat is the length of saturated zone (m) [section 4.1.8].

4.1.2. Maximum aquifer volume

The aquifer volume (m^3) when full is estimated as:

Equation 65: AqVolMax = Hsoil * Lslope * Lwet
Hsoil is the aquifer depth (m) [section 4.1.3].
Lsope is the length of slope (m) [section 4.1.7].
Lwet is the length of wetland cathment (m) [section 4.1.6].

The actual aquifer volume (m^3) is estimated each day as outlined in section 4.2.1.

4.1.3. Aquifer saturated hydraulic conductivity.

The saturated hydraulic conductivity of the aquifer is based on the sub-soil clay content of the soils in the block, and is estimated as:

Equation 66: $\text{ksatAq} = 14611\ \text{clay}^{-3.4868}$

clay is subsoil clay content (%) [section 2.1.3].

ksatAq has values of 4.763, 0.425, 0.103 and 0.038 m/day at 10, 20, 30 and 40% clay respectively.

4.1.4. Aquitard depth

The thickness of the conceptual aquifer (Hsoil) is the depth of soil overlying the shallowest aquitard (viz., layer of low permeability). Thus, Hsoil is the depth (m) down to the layer that is impervious to soil water, or where soil drainage is very slow. As a first approximation, this is the depth to the water table in summer, or the depth of any compacted layer or hard pan encountered while excavating (e.g., digging strainer post holes). A conservative estimate of Hsoil is the depth of the *A*-horizon. In riparian filter strips the water table may lie close to the surface and Hsoil can be approximated by bank height. Seepage from road cuttings can also indicate the aquitard depth. In pallic soils, aquitard depth is usually < 1 m.

The wetland sub-model uses ranges as inputs, with the ranges being 0-1 m, 1-2 m, 2-3 m, 3-5 m, and > 5 m, which corresponds to an aquitard depth of 0.5 m, 1.5 m, 2.5 m, 4 m, and 7 m respectively. If no depth is selected, then the default aquitard depth is 4 m (3-5 m range)

4.1.5. Aquifer water height

The aquifer water height Hres (m) is estimated daily as:

Equation 67:

$$\text{Hres} = \begin{cases} \text{Hsoil} / (2 * (1 - \text{AqVol} / \text{AqVolMax})) & \text{AqVol} > \text{AqVolMax}/2 \\ 2 * \text{AqVol} / \text{Lslope} / \text{Lwet} & \text{otherwise} \end{cases}$$

AqVol is the aquitard volume (m^3) [section 4.1.1].
AqVolMax is the maximum aquitard volume (m^3) [section 4.1.2].
Hsoil is the aquifer depth (m) [section 4.1.3].
Lslope is the length of slope (m) [section 4.1.7].
Lwet is the length of wetland cathment (m) [section 4.1.6].

The relationship between Hres/Hsoil and the proportion of the aquifer that is filled (AqVol/AqVolMax) is shown in Figure 7.

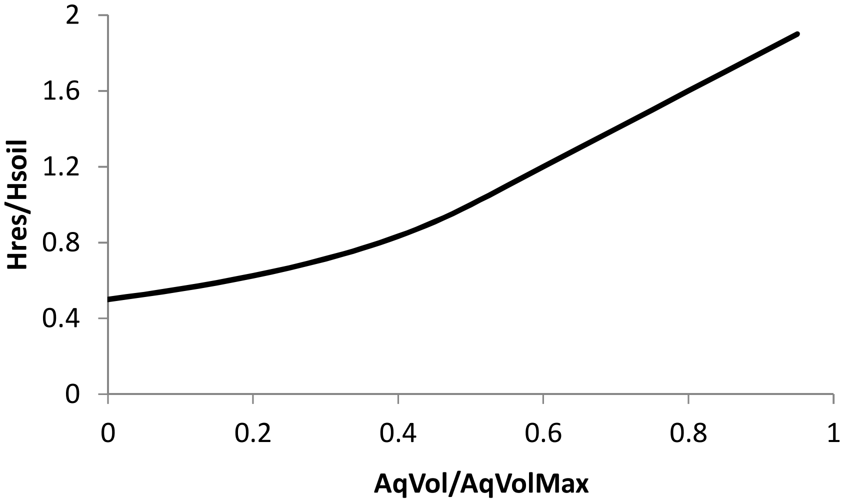

Figure 7. Relationship between AqVol/AqVolMax and Hsoil/Hres.

The aquifer water height is initialised for time 0 as it is required for an initial estimate of aquifer volume. Thus:

Equation 68: Hres = (phi * SumROdrain / 1000 / 365) * Lslope / sKsat

phi is the portion of re-emergent flow [section 4.1.9].

SumROdrain is the sum of drainage from each block (mm).

365 is days in year.

Lsope is the length of slope (m) [section 4.1.7].

1000 comverts mm to m.

and where sKsat is estimated as:

Equation 69: sKsat = hillslope * ksatAq

ksatAq is the aquifer saturated hydraulic conductivity (m/d) [section 4.1.3].

hillslope is the average hill slope [section 2.4.2].

If the initial Hres (Equation 68) is greater than the aquitard depth Hsoil (section 4.1.3), then Hres is recalculated as:

Equation 70: Hres = SQRT(phi * SumROdrain /1000 /365 * Lslope * Hsoil / sKsat)

phi is the portion of re-emergent flow [section 4.1.9].

SumROdrain is the sum of drainage from each block (mm).

1000 comverts mm to m.

365 is days in year.

Lsope is the length of slope (m) [section 4.1.7].

Hsoil is the aquifer depth (m) [section 4.1.3].

sKsat is the hillslope adjusted aquifer saturated hydraulic [Equation 69].

4.1.6. Length of wetland catchment

If the wetland catchment area is assumed square, then the length of the wetland catchment (m) can be assumed to be:

Equation 71: Lwet = SQRT(WetCatchArea * 10000)
WetCatchArea is the entered wetland catchment area (ha).
10000 converts ha to m^2.

4.1.7. Length of slope

If the wetland catchment area is assumed square, and hill slopes occur on both sides, then the length of the slope (m) of the aquifer on one side can be assumed to be:

Equation 72: Lslope = Lwet/2
Lwet is the length of wetland cathment (m) [section 4.1.6].

4.1.8. Length of saturation zone

If the aquifer water height exceeds the aquitard depth, the aquifer becomes saturated for a length (m) as:

Equation 73: Lsat = 0 Hres < Hsoil
= Lslope * (1 - Hsoil/Hres) otherwise
Lslope is the length of slope (m) [section 4.1.7].
Hsoil is the aquitard depth (m) [section 4.1.3].
Hres is the aquifer water height (m) [section 4.1.5].

4.1.9. Proportion of re-emergent flow

The estimation of the proportion of total sub-surface flow that re-emerges within the catchment poses a serious challenge.

The wetland flow type defines the amount of flow that occurs within the wetland (Table 13). Wetland flow type and wetland/catchment area give an indication of the proportion of re-emergent flow that is occurring. Based on experience from a few locations, the proportion of re-emergent flow was estimate as shown in Table 14.

Table 13. Definition of wetland flow types.

Type	Wetness	Vegetation	Stock
Type A	Water always flows.	Dominated by sedges and reeds. May contain flaxes, willows, etc.	Easily damaged by mob stocking of cattle. Avoided by sheep.
Type B	Flows most of the year. Dry in drought.	Abundant sedges and rushes.	Moderate pugging if cattle have access all year. Avoided by sheep in winter
Type C	Flows in autumn, winter and spring. Dry in summer	Abundant sedges and reeds. Some pasture grasses	Pugging in winter if cattle have access. Grazed by sheep much of the year.
Type D	Only flows during rain.	Dominated by pasture grasses.	Grazed by sheep all year.

Table 14. Proportion, expressed as a percentage, of re-emergent flow as a function of wetland flow and wetland/catchment area ratio.

Wetland flow	Wetland/catchment area ratio				
type	< 0.01	0.01-0.02	0.02-0.04	0.04-.06	> 0.06
Type A	5	15	20	25	30
Type B	3	10	15	20	25
Type C	2	3	5	10	15
Type D	1	2	3	5	10

If wetland flow is unknown, then the rate at which the soil conducts shallow groundwater could be based on current soil profile drainage class and hence the proportion of total sub-surface flow estimated (Table 15). It should be noted that soil profile drainage class is not necessarily a good measure of permeability and hence the first option is preferred. Re-emerging flow is determined by the combination of the depth of the aquitard and the rate at which the soil conducts shallow groundwater down slope.

Table 15. Proportion, expressed as a percentage, of re-emergent flow as a function of drainage class and aquitard depth.

Profile drainage class	Aquitard depth (m)				
	0-1	1-2	2-3	3-5	> 5
Well	10	5	3	1	1
Moderately well	15	10	5	3	3
Imperfect	20	15	10	5	3
Poor	25	20	15	10	5
Very poor	30	25	20	15	10

4.2. Aquifer drainage flows

4.2.1. Input from the root zone

Drainage flow from the root zone to the aquifer (m^3/day) is estimated as:

Equation 74: $Qdrainageinput = WtROrootdrain / 1000 * Lslope * Lwet$

WtROrootdrain (mm/day) is the block weighted average drainage input [section 4.2.2].

1000 is the conversion mm to m.

Lwet is the length of wetland (m) [section 4.1.6].

Lsope is the length of slope (m) [section 4.1.7].

4.2.2. Block weighted drainage

The drainage input from a catchment into the reservoir can come from more than one block. The proportion of blocks contributing to drainage can be specified by the user, or a default allocation is assumed. Thus:

Equation 75: $WtROrootdrain = \sum_{block}((ROrootdrain_{block} * Contarea_{block}) / \sum_{block}(Contarea_{block}))$

ROrootdrain is the drainage below the rootzone (mm/day) [section 3.6].

and

Equation 76: $Contarea = prop_{block} * area_{block}$

prop is the proportion of block area contributing to catchment.

area is the block area (ha).

The proportion of block area contributing to catchment is a user input, and can include areas outside the wetland, or by default is estimated as:

Equation 77: $prop_{block} = barea_{block} / \sum_{block} barea$

where

Equation 78:

barea	$= 0$	wetland or riparian block
	$= (1 - propdrain) * area_{block}$	drainage method selected
	$= area_{block}$	otherwise

area is the block area (ha).

propdrain is the proportion of drainage below the root zone that ends up in drains (0-1) for a given block.

4.2.3. Deep drainage flow

Deep drainage (m^3/day) may emerge further down the catchment as spring flow but is not amenable to nutrient mitigation by filter strips and wetlands within the farm catchment. The nutrient content of deep drainage may be attenuated by wetlands elsewhere in the catchment. The flow that re-emerges within the catchment is assumed to be a constant proportion of the total sub-surface flow, hence:

Equation 79: $Qdeep = (1 - phi) * Qdrainageinput$

phi is the proportion of re-emergent flow [section 4.1.9].

Qdrainageinput is the drainage input (m^3/day) [section 4.2.1].

4.2.4. Bank flow

Seepage (m^3/day) from the aquifer occurs daily following Darcy's law. Thus:

Equation 80: Qbank = ksatAq * hillslope * Hsoil * Lwet Hres > Hsoil
= ksatAq * hillslope *
Hres * Lwet otherwise
ksatAq is the saturated hydraulic conductivity (m/d) [section 4.1.3].
hillslope is the average hill slope [section 2.4.2].
Hsoil is the aquitard depth (m) [section 4.1.3].
Hres is the aquifer water height (m) [section 4.1.5].
Lwet is the length of wetland (m) [section 4.1.6].

4.2.5. Exfiltration flow

Exfiltration is flow (m^3/day) from the saturation part of the aquifer. Exfiltration does not affect the total volume of shallow sub-surface flow that enters the riparian wetland but it does affect the flow pathway. Currently no attenuation occurs along either pathway and exfiltration is ignored. However, in the future surface (exfiltration) and sub-surface flow may be treated differently within the wetland sub-model.

Equation 81: Qexfilt = ksatAq * hillslope * (Hres - Hsoil) * Lwet Hres > Hsoil
= 0 otherwise
ksatAq is the saturated hydraulic conductivity (m/d) [section 4.1.3].
hillslope is the average hill slope [section 2.4.2].
Hsoil is the aquitard depth (m) [section 4.1.3].
Hres is the aquifer water height (m) [section 4.1.5].
Lwet is the length of wetland (m) [section 4.1.6].

4.2.6. Reject flow

If drainage into the aquifer occurs when the aquifer is saturated, then a portion of the drainage to the deep aquifer is rejected from the aquifer (see Figure 6).

Equation 82: Qreject = phi * WtROrootdrain / 1000 * Lwet * Lsat
phi is the proportion of re-emergent flow [section 4.1.9].
WtROrootdrain (mm/day) is the block weighted average drainage input [section 4.2.1].
Lwet is the length of wetland (m) [section 4.1.6].
Lsat is the length of saturated zone (m) [section 4.1.8].

5. Drainage from artificially drained systems

Tile drains are fed by drainage flow through the soil matrix and water flux tends to increase gradually during the drainage season. Nutrient concentration tend to increase gradually during the first part of the drainage season, and then to taper off.

Mole drainage occurs on heavy clay soils throughout the country. It results in preferential flow down the slots created by the moler, which reduces surface flow. Water and nutrient appear in the drains earlier in the season (via preferential flow) than with tile drains (dominated by matrix flow).

5.1. Proportion of drainage to drains

The proportion of drainage below the root zone that ends up in drains is a measure of the effectiveness of the drainage system and is estimated as:

Equation 83: $\text{propdrain} = \text{pdrained} * \text{fspacing} * \text{fage}$

pdrained is the entered fraction of the block that is artificially drained (0-1).
fspacing is the factor for drain spacing (0-1) [section 5.3].
fage is typical effeciently of fully drained system (0-1) [section 5.5].

If artificial drainage is not selected, propdrain is set to one. It is assumed that the maximum effectiveness is 80%.

5.2. Flow to drains

Drainage is implemented on a block basis. The default assumption is that drainage flow equals total flow from the drained area plus shallow groundwater and surface flow from the remainder of the catchment (Rutherford *et al*., 2008). This can be modified using the drain spacing and drain depth if known. Hence, the flow to drains (m^3) is estimated as:

Equation 84:

$$\begin{aligned}\text{Qdrain} &= \text{propdrain}_{\text{block}} * \text{area}_{\text{block}} * \text{ROrootdrain} \\ &+ (1 - \text{propdrain}) * \text{area}_{\text{block}} * \text{ROsurface} \\ &+ (1 - \text{propdrain}) * \text{area}_{\text{block}} * \text{fdraindepth} * \text{ROshallow}\end{aligned}$$

propdrain is the proportion of drainage below the root zone that ends up in drains (0-1) for a given block.
$\text{area}_{\text{block}}$ is the block ha (ha). including rotating fodder crops.
fdraindepth is the factor for drain depth (0-1) [section 5.4].
ROrootdrain is runoff below the soil profile (mm/day) [section 3.6].
ROsurface is surface runoff (mm/day) [section 3.5].
ROshallow is runoff to shallow ground water.

On drained areas, the surface threshold (section 3.5.1) is increase with drainage, and hence runoff is minimal. If it is assumed that runoff from both the drained and undrained part does not join the drainage system, and it is assumed that the drains are above the shallow groundwater, then drainage can be simplified to:

Equation 85: $\text{Qdrain} = \text{propdrain}_{\text{block}} * \text{area}_{\text{block}} * \text{ROrootdrain}$

All flow through the drainage system is directly to streams unless routed through an artificial wetland.

5.3. Efficiency of drainage

The default assumption is that the efficacy of a field-drained system excluding mole/tile drainage, is based on recommended spacings between drain lines (Rutherford *et al.*, 2008). According to the Novaflo® manual, the standard design is for a spacing of 20 m for cattle and 60 m for sheep. For example if the drain spacing is 40 m in land where 20 m is recommended, drain flow will be reduced by 50%. If drain spacing is unknown (not entered), default values will be assumed: 20 m for dairy/cattle and 60 m for sheep.

Therefore, the user can specify drain spacing, or a default based on recommended spacing's is assumed.

Equation 86: fspacing = Dguide / DrainSpace   DrainSpace > 0
= 1   DrainSpace = 0
Dguide is the recommended drain spacing (m).
DrainSpace is an input value (m).

The factor (1 - fspacing) is the fraction of runoff from the drained part of the catchment that becomes drainage to the aquifer.

The recommended drain spacing varies with soil texture (Table 16). Hence, Dguide (m) was based on a relationship with clay content if drainage depth was supplied, or based on a recommended spacing of 60 m for sheep farms and 20 m for dairy farms (Equation 87).

Equation 87: Dguide = 26.168 * exp(-0.0364 * clay) * 2   Draindepth < 0.9 m
= 41.143 * exp(-0.0421 * clay) * 2   Draindepth > 0.9 m
= 60 * pIntake + 20 * (1 - pIntake)   otherwise
Clay is subsoil clay content (%) [section 2.1.3].

where:

Equation 88: pIntake = $(\text{BlockSU}_{\text{sheep}} + \text{BlockSU}_{\text{Deer}} + \text{BlockSU}_{\text{Dairygoats}} + \text{BlockSU}_{\text{Other}}) / 100$
BlockSU is the percentage of block intake by a particular animal type.

Table 16. Guideline drain spacing.

Soil texture	Effective drain spacing each side of the pipe		General description of permeability
	H_{drain} 0.6-0.9 m	H_{drain} 0.9-1.2 m	
Sand	15-23	23-46	Medium/high
Sandy loam	12-15	15-23	Medium
Loam	11-14	12-15	Medium/low
Clay loam	6-9	8-11	Low
Sandy clay	5-6	6-8	Very low
Clay	3-5	5	Very low, practically impermeable

Source: Iplex (2007)

To illustrate this approach, at Toenepi (clay loam subsoil) the recommended spacing for drains 0.9-1.2 m deep is 8-11 m each side of the pipe, so drain spacing needs to be 16-22 m. Actual drain spacing at one farm was 41 m. Thus during the drainage season (May-Nov) drainage flow from the artificially drained land is about 50% of total runoff.

5.4. Depth of drains

If the depth to the aquitard is greater than the depth to the drains, then a proportion of the groundwater flow from the undrained part of the catchment may pass underneath the artificial drains (Rutherford *et al.*, 2008). If drain depth is known, then

Equation 89: fdraindepth = Hdrain / Hsoil
Hdrain is the depth to drain (m).
Hsoil is the aquitard water depth (m) [section 4.1.5].

Currently, depth to the drain compared to the aquitard depth is not activated within the wetland sub-model (fdraindepth = 1).

5.5. Age of drains

Although the efficiency of the drainage system probably decreases with age, it is assumed that it has a constant value is 1 in both mole and field drained systems.

6. References

Cichota R, Brown H, Snow V O, Wheeler D M, Hedderley D, Zyskowski R, and Thomas S 2010 A nitrogen balance model for environmental accountability in cropping systems. New Zealand Journal of Crop and Horticultural Science 38: 189-207.

Iplex, 2007 Novaflo Land Drainage Pipe Technical Manual. http://www.iplex.co.nz/ftp/pdfs/nexus_and_novaflo_installation.pdf. Accessed 28 August 2007.

Irrigation New Zealand 2014 New Zealand Irrigation Overview, Book 1, Irrigation New Zealand.

Martin R J 1990 Measurement of water use and pasture growth on Templeton silt loam. New Zealand Journal of Agricultural Research 33: 343-349.

McAneney K J, Judd M J and Weeda W C 1982 Loss in monthly pasture production resulting from dryland conditions in the Waikato. New Zealand Journal of Agricultural Research 25: 151-156.

McDowell R W and Rowley D 2008 The fate of phosphorus under contrasting border-check irrigation regimes. Australian Journal of Soil Research: 46: 309–314

Milne J D G, Clayden B, Singleton P L, and Wilson A D 1995 Soil Description Handbook. Revised edition. Manaaki Whenua Press, 157 pp.

Monaghan R M, Carey P L, Wilcock R J, Drewry J J, Houlbrooke D J, Quinn J M, and Thorrold B S 2009 Linkages between land management activities and stream water quality in a borderdyke-irrigated pastoral catchment. Agriculture, Ecosystems and Environment 129: 201-211.

Parfit R L, Joe E N, and Cook F J 1985a Water use and pasture production on Judgeford silt loam. New Zealand Journal of Agricultural Research 28: 387-392.

Parfit R L, Roberts A H C, Thomson N A, and Cook F J 1985b Water use, irrigation, and pasture production on Stratford silt loam. New Zealand Journal of Agricultural Research 28: 393-401.

Porteous A S, Basher R E, and Salinger M J 1994 Calibration and performance of a single-layer soil water balance model for pasture sites. New Zealand Journal of Agricultural Research 37: 107-118.

Rutherford K, McKergow L, and Rupp D 2008 Nutrient attenuation and hydrology modules for Overseer. NIWA Client Report: HAM2008-088. 75 pages.

Rutherford K and Wheeler D 2011 Wetland nitrogen removal modules in OVERSEER® In: Adding to the knowledge base for the nutrient manager. Eds. Currie L D and Christensen C L. http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 12 pages.

Wilde R H and Ross C W 1996 New Zealand Reference Soil Collection and the National Soils Database. New Zealand Soil News 44: 224–227.