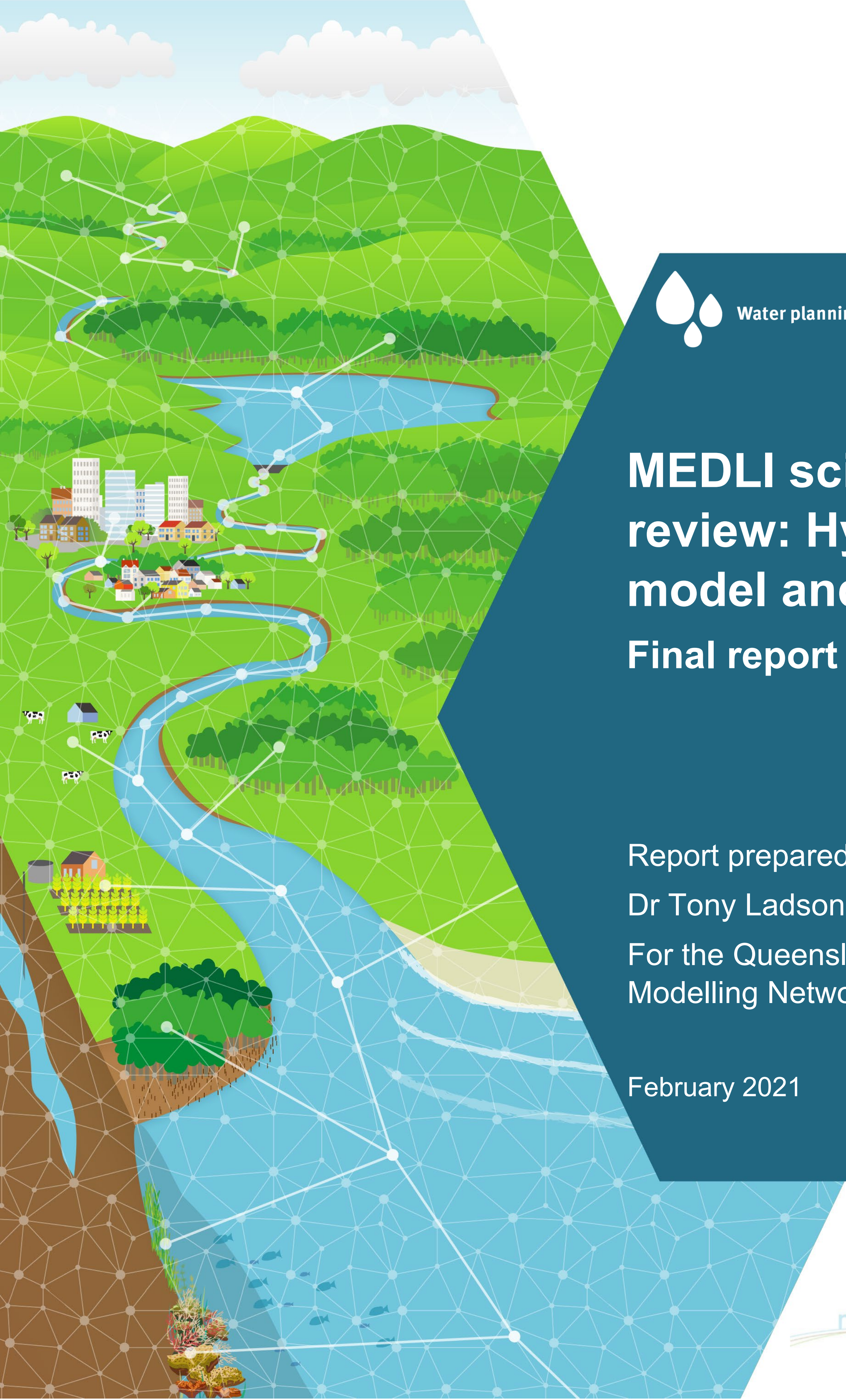
QUEENSLAND WATER MODELLING NETWORK



Water planning, integration and management

MEDLI science review: Hydrology - model and process

Final report

Report prepared by
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For the Queensland Water Modelling Network

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moroka
Queensland Government

The Queensland Water Modelling Network (QWMN) is an initiative of the Queensland Government that aims to improve the state's capacity to model its surface water and groundwater resources and their quality. The QWMN is led by the Department of Environment and Science with key links across industry, research and government.

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Acknowledgements

QWMN commissioned a review of MEDLI (Model for Effluent Disposal using Land Irrigation) to assess the science underpinning its Hydrology, Nutrient & Pond Chemistry modules, to identify gaps, and suggest possible improvements. This report is one of five reports written for the MEDLI Science Review by a team led by Prof Ted Gardner (Victoria University). Other reports from the MEDLI Science Review are "Pond chemistry module" by Dr Mike Johns and Dr Bronwen Butler, "Methodologies used by biophysical models for simulating soil nutrient pools and processes in pasture systems - Carbon, nitrogen and phosphorus" by Dr Phil Moody, "MEDLI Science Review: Synthesis" by Ted Gardner and "Modelling of Water and Solute Transport in MEDLI" by Prof Freeman Cook.

Summary

This document provides an assessment of hydrologic aspects of MEDLI (Model for Effluent Disposal using Land Irrigation), a review of hydrologic models similar to MEDLI and information on selected key processes relevant to the systems that MEDLI is used to model.

Eighteen models were reviewed to examine a range of questions including: the method used to partition rainfall into runoff and infiltration, model temporal and spatial scale, the approach to estimating potential evapotranspiration, simulation of soil water redistribution, required soil hydraulic properties, modelling of erosion and calculations of the enrichment ratio used to estimate export of sediment attached nutrients.

Two general distinctions were observed. In terms of temporal scale, there was a division between those models focused on representing events and those intended for continuous simulation. Models could also be divided into two groups in terms of their approach to simulating the redistribution of soil water. One class of models routed soil moisture through a number of soil layers while a more sophisticated approach was to numerically solve Richards equation and the advection-dispersion equation to determine solute movement.

Following the model review, three key processes were considered in detail: deep drainage, leaching of nitrate and the effect of crop residual and cover on soil evaporation. This included an assessment of the approaches taken in other models, combined with a review of the literature.

This information can now be considered, along with related reports, to assess whether any enhancements to MEDLI are warranted.

Issues raised in this report have been summarised in Table 1, along with their implications.

The review also contains a comprehensive table of the modelling approaches (Table A1) used to describe hydrology/leaching/erosion in 18 main-stream hydrology models which would be a fundamental resource for modellers who are thinking of improving existing models or building new models. Table A1 also highlights the seminal work of the USDA and EPA 1980s models on which most daily time step models are based to a lesser or greater degree today. “*Indeed, old algorithms are not superseded algorithms* “.

Table 1. Strategic overview of the issues and implications raised by this review of 18 hydrologic models, with additional insights from the Synthesis Report (Gardner 2021) (From p.14)

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
Infiltration /runoff	The infiltration/runoff module uses SCS Curve number (CN) approach which is a well-tested infiltration model for dryland soils but not irrigated soils.	Curve Number (CN) approach is used in MEDLI and in 9 of the models reviewed. It assumes that there is a maximum amount of water that can be retained (“S” mm) by the soil before runoff commences. CN is scaled to 100 when S = 0 and falls towards 35 as S increases. Only daily rainfall data is required plus adjustment to CN for soil texture and stubble cover.	Alternative infiltration models suggested are the Green-Ampt infiltration model and the fundamental Richards equation. Green-Ampt has the ability to consider sub daily time steps, without the cost of needing lots of new soil input parameters. But its solution for time varying rainfall is complex. (Cook 2021 discusses this in more detail).	Both equations require more complex soil hydraulic properties than CN and more complex numerical solutions. APSIM provides a relatively simple method to obtain the soil water hydraulic properties needed for the Richards equation (see Huth et al. 2012)	Potentially high. Cook 2021 has provided a methodology to solve the Green-Ampt implicit equation for variable rainfall rates.	Infiltration is critically important in hydrology models as it determines recharge of the soil water deficit.	Investigate inclusion of this code. Use a similar experimental protocol as that used for dryland paddocks in Queensland.
Transpiration	The use of Class A pan is being phased out by BOM in favour of Penman-Monteith equation. FAO 56 no longer recommends Class A pan.	MEDLI uses Class A pan data provided directly from the SILO Australian climate data base (which is taken from BOM).	1) Potential evapotranspiration (PET) can be estimated using the more physically rigorous Penman, Penman-Monteith, and Priestly-Taylor equations. 2) Continue to use Class A Pan in MEDLI by using SILO website synthetic pan data.	1) Testing would be needed to compare Class A Pan data with Penman-Monteith data from SILO. This should be followed by testing MEDLI outputs using paired Class A pan and PM data. Note that the crop coefficients will change between models to deliver the same Transpiration for a given climate data set. 2) No change	Tedious testing but not particularly computationally difficult.	Errors in Evapotranspiration will spill over to errors in the whole water balance, especially under irrigated conditions. Important that Penman-Monteith does not generate different water balance (to Class A pan) on test data sets.	Class A pan should be retained as the potential to get non-corresponding results is quite high. This in turn will require extensive fine tuning of MEDLI algorithms. SILO is handling the phasing out of Class A pan data by generating synthetic pan values from BOM weather data.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
Effect of crop residue and cover on soil evaporation	Green and dead cover are assumed to have the same effect on reducing potential soil evaporation. Experimental data shows that dead biomass (kg/ha) is much more important in reducing evaporation than % dead cover.	The proportion of soil that has green (transpiring) cover is assumed to have no soil evaporation. The same assumption applies to dead surface cover (e.g., mulch) as it makes no allowance for the thickness or mass. That is, a 1 mm thickness of dead cover is assumed to be as effective in reducing evaporation as a 10 mm thickness, for equal soil cover %s	Adopt the HowLeaky evaporation algorithm which explicitly considers residue mass on evaporation reduction. This is much more physically realistic.	Simple change.	Low	Underestimating soil evaporation due to complete, but thin, dead cover can translate into underestimating Irrigation Demand by up to 100 mm/yr. in SEQ	Adopt HowLeaky dead cover algorithm in MEDLI
Soil Evaporation	None.	Bare soil evaporation is predicted using Richie's 2-stage soil evaporation algorithm. Stage I involves demand-driven soil evaporation at the potential evaporation rate. Stage II is supply driven, and evaporation continues much more slowly. Its rate is estimated as a function of the square-root of time since rainfall.	None. No action to be taken.	None. Evaporation has been well studied in Queensland by Jenny Foley so no need for more of this technically difficult experimentation	Not applicable.	Not applicable.	Retain Ritchie's soil evaporation algorithm.
Erosion and sediment enrichment	Erosion and sediment enrichment is not currently modelled in MEDLI. But it is considered in model such as HowLeaky and APSIM.	Erosion and sediment enrichment is not modelled in MEDLI.	Consider inclusion of Enrichment Ratio as per HowLeaky.	Implementation would allow nutrient enrichment in runoff to be predicted	Potential high, especially since mass balance considerations will need to be addressed.	Low Erosion is unlikely to be an issue in pasture dominant irrigated effluent disposal	Review options for inclusion.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
Loss of N & P in surface runoff	Surface runoff will export DIN (dissolved inorganic nitrogen) and ortho-phosphate.	None.	For nitrogen, use N loss algorithm from HowLeaky and GRASP. For phosphorus, use the P loss in runoff algorithm described in Moody 2021).	Mass flux of dissolved N & P likely to be small except when rainfall runoff shortly follows effluent irrigation. However, concentrations could exceed ANZECC standards.	Moderate.	Moderate.	Incorporate these two-simple algorithms into MEDLI.
Redistribution of soil water down the profile / Drainage	1)Drainage module is empirical but can give the correct time trend of soil drainage. However, Cook (2021) argues that the shape of the draining soil water profile is incorrect. The issue needs more desktop investigation. 2) Excessive deep drainage **may** occur on the first irrigation of the cropping season if shrinkage cracks link up with permanent deep sub soil structural cracks (slickensides). Soil physics theory cannot predict this behaviour. A review of deep drainage literature (e.g., research in southern QLD and NSW by Silburn, Montgomery and others) may show if the first irrigation of the season leads to infiltration	A 1-dimensional cascading bucket model moves water in excess of "Field Capacity" downward through the soil profile, modified by the saturated hydraulic conductivity of each defined "soil layer". The algorithm reproduces the expected non-linear reduction in drainage rate with elapsed time.	1) The Richards equation is a more sophisticated approach, and only used by one of the reviewed models (APSIM-SWIM). Cook (2021) suggests the Sisson model will better capture both the time trend of drainage rate and the shape of the soil water profile for a modest increase in data inputs & computational complexity.	Deep drainage and solute leaching are important outputs of the MEDLI model. They need to be as correct as practically possible. It's possible the incorrect soil moisture profile shape will affect solute leaching predictions	Moderate.	1) Very important. Upgrading the drainage algorithm in MEDLI is considered to be of high priority. (2) No relevance to effluent irrigated pasture	Investigate inclusion through further post-graduate research.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
	far exceeding soil water deficit.						
Upflow	No consideration of upflow from a groundwater table nor from a wetter subsoil relative to soil surface moisture content.	Deep drainage is predicted using a one-dimensional cascading bucket model.	Consider the approach used in APSIM using a simple Diffusivity parameter and a water content gradient.	Potentially not too much extra complexity but need investigation.	Potentially difficult	Only relevant for irrigated soils with a water table < 1 .5 m deep.	No further action.
Leaching of nitrate	Leaching of solutes (nitrate) done too simplistically in MEDLI. Differential solute movement through the soil pores (of different diameters) and lateral flows are not considered.	N leaching calculated from predicted deep drainage and the predicted nitrate-N concentration in the lowest soil layer. Lateral flow of water and nitrate is ignored.	(1) A simple convective one-dimensional flow model adjusted for mobile soil water content, deep drainage below the root zone and **mass** of nitrate above the root zone as per Burns 1975, Corwin et al. 1991 and Scotter et al. 1993. (2) A Transfer Function approach can capture the variation in solute velocity between soil pores which cause a diffuse solute front similar to that observed and predicted by convective-dispersion (CD) theory, but without the computational complexity of the CD equation. But this requires calibration with another solute leaching data set.	(1) The key insight is the need to define the **mobile water fraction** that moves most of the nitrate via convective flow. More detail on concentrations by soil depth and time can be obtained by the Scotter et al.'s 1993 improvement of the Burns model. Adding these concepts to MEDLI could be done relatively easily. (2) Transfer Function models has no future in MEDLI Lateral flow is too complex for most users of MEDLI. But lateral flow is more likely to occur in sloping Duplex soils in winter dominant rainfall where Rain >> ET for months.	(1) Easy but need to estimate mobile water as a fraction of the DUL moisture content. (2) High.	(1) High importance as nitrate leaching a key MEDLI output. (2) Low except in southern Australia where Rain >> ET for months.	The drainage algorithm (based on cascading buckets) needs improvement as per the Cook (2021) review.

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Abbreviations

Abbreviations	
DUL	Drained upper limit of soil (aka field capacity)
ESW	Extractable Soil Water
ET	Evapotranspiration
LL	Lower limit of plant available water (aka permanent wilting point)
MEDLI	Model for Effluent Disposal Using Land Irrigation
PET	Potential Evapotranspiration
SAT	Saturated water content of soil
USLE	Universal Soil Loss Equation

Definitions of soil properties

Soil Water Status	Soil Water Potential (bars)	Soil Water Potential (kPa)
Saturation	0	0
Field capacity	-1/3	-33
• Permanent wilting point • Lower limit of plant available water	-15	-1500
Air-dry soil	-31	-3100

1. Introduction

This report is one of several that provides a broad review of MEDLI (Model for Effluent Disposal using Land Irrigation). The focus here is on hydrologic aspects, and the report assesses if they are fit-for-purpose and documents revisions that should be considered.

This work is in two parts. First, a review of 18 models is presented. These have similar capability, or seek to answer similar questions, as MEDLI. Second, a review has been undertaken of three processes that represent important components of the MEDLI model. These are deep drainage, leaching of nitrate and the influence of crop and residue cover on soil evaporation.

1.1. Report outline

Following this introduction, Section 2 summarises the review of models with details provided in a series of tables in Appendix A. Section 3 discusses deep drainage and nitrogen leaching. Section 4 examines the influence of crop residual and cover on soil evaporation.

2. Review of models

At the request of the MEDLI review panel, a review was undertaken of 18 models with similar capability as MEDLI. These are:

1. AGNPS (Agricultural Nonpoint Source)
2. ANSWERS (Areal Nonpoint Source Watershed Environmental Simulation)
3. APSIM (Agricultural Production System Simulator)
4. CERES (Crop Estimation through Resource and Environment Synthesis)
5. CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems)
6. EPIC (Erosion Productivity Impact Calculator)
7. GLEAMS (Groundwater Loading Effects of Agricultural Management Systems)
8. GRASP (Grass Production)
9. HowLeaky
10. HSPF (Hydrologic Simulation Program Fortran)
11. HYDRUS – 1D
12. LEACHM (Leaching Estimation And Chemistry Model)
13. OVERSEER
14. PERFECT (Productivity Erosion Runoff Functions to Evaluate Conservation Techniques)
15. RUSLE (Revised Universal Soil Loss Equation)
16. SWAT (Soil and Water Assessment Tool)
17. SWIM (Soil Water Infiltration and Movement)
18. WEPP (Water Erosion Prediction Project)

For each of these models the following aspects were investigated and summarised:

1. Infiltration/runoff process

2. If the curve number approach was used to determine runoff how did the retention parameter vary with soil moisture.
3. Temporal modelling approach, either event based, continuous, growing season or other
4. Model time step
5. Spatial scale (e.g., field scale or catchment scale) whether the model is 1D (point) or 2D (grid)
6. Potential evapotranspiration (e.g., Pan, Penman-Monteith, Priestly-Taylor)
7. The method used by the model to redistribute soil water
8. Transpiration
9. The relationship between transpiration rate and soil moisture
10. Erosion, sediment generation and transport
11. Whether a sediment enrichment ratio is used as part of simulating transport of sediment attached nutrients and pollutants and how the ratio is estimated
12. Phosphorus export (whether included in model and the approach)
13. Nitrogen export (whether included in model and the approach)
14. The soil hydraulic properties that are required to be input by the user
15. Deep drainage
16. Solute movement
17. Nitrate leaching
18. Limitations of the model
19. Comments
20. References

The results of this review are provided in Appendix A and in a spreadsheet that accompanies this report.

Some key findings are discussed below with further detail provided on deep drainage, nitrogen leaching and soil evaporation in the following sections.

2.1. General

In reviewing these 18 models, two general distinctions were apparent:

- Temporal scale of simulation
- The method of solution used to determine the distribution of soil moisture.

2.1.1. Temporal scale

First, in terms of temporal scale, models were focussed at:

- Individual events
- Particular periods e.g., a crop growing cycle, or
- Continuous simulation.

For example, the focus of ANSWERS (Beasley and Huggins, 1982) is to simulate erosion from individual events. LEACHM (Hutson and Wagenet, 1995) is focused on a single growing season and EPIC (Williams et al., 1984) aims to examine the influence of erosion on crop production over time periods of, possibly, centuries. Two of the well-established event models had been updated to include continuous versions, ANSWERS-continuous and AnnAGNPS.

The choice of temporal scale influences the processes that need to be modelled. For example, evaporation, redistribution of water in the soil profile, and deep drainage are less important at the event scale where the focus is on peak flow rates, event hydrographs and associated processes such as sediment detachment and transport.

Generally, those models that operate over continuous time periods have larger time steps, usually daily. The advantage of daily time steps is that climate data is readily available. The network of stations collecting sub-daily weather data is comparatively sparse. However, some processes, such as erosion events, are driven by sub-daily rainfall intensity. Incorporating the simulation of erosion into a model with a daily time step means that sub-daily rainfall intensity may need to be estimated from daily rainfall data (e.g., Fraser et al., 2011).

2.1.2. Solution approach

A second key difference between models is the mathematical approach to determining the on-going distribution of water in the soil profile including infiltration, evaporation, redistribution and deep drainage. There were two main approaches:

- Numerical solution to Richards equation, generally combined with the advection-dispersion equation to calculate solute movement. This approach was used in, HYDRUS, LEACHM, SWIM and APSIM-SWIM
- Routing of water through a series of 4 to 10 soil layers (most models including MEDLI).

The Richards equation approach is more sophisticated and mathematically correct but is more complex. Traditionally, run times have been inconveniently long to solve the Richards equation but this is becoming less of an issue as computers become more capable. There is an analogy here to the distinction between hydrologic and hydraulic modelling of flood flows. Both these approaches are based on solution to the partial differential equations of fluid flow (the Navier-Stokes equations) with different levels of simplification. In hydrologic modelling, only the solution of the continuity equation is required, while for hydraulic modelling the St Venant equations are solved. Two-dimensional hydraulic modelling was impractical when the 3rd edition of Australian Rainfall and Runoff was published in 1987 (Pilgrim, 1987) but at the time of the 4th edition (Ball et al., 2016) it was the dominant approach to determine flood depths, extents and velocities. It is more flexible, accurate and the two-dimensional nature of the solutions is much easier to communicate graphically. Software providers have developed several very capable models with excellent graphical outputs. The inputs, mainly detailed topographical data, are now straightforward to obtain. However, the use of hydraulic models does require expertise and licence fees are a barrier to casual use meaning modelling work is usually done by specialist consultancies.

The lesson here is that models that directly solve the Richards equation are likely to become faster and easier to use so it is important to keep track of their development. At this stage, there was only one model amongst those reviewed that coupled a Richards equation approach to simulating soil water redistribution with sediment detachment and transport - APSIM-SWIM. This was applied successfully to estimate deep drainage and nitrate leaching under sugarcane in the Burdekin Delta (Stewart et al., 2006).

2.2. Infiltration/runoff process

There were three main approaches to partitioning rainfall between runoff and infiltration:

- Curve number
- Richard equation
- Green and Ampt equation

The SCS Curve number approach was used in 9 of the 18 models that were reviewed and is used in MEDLI (see Section 2.2.1 for more details). Note that the curve number approach is a simplification to allow the prediction of runoff when only daily rainfall is known. If sub-daily rainfall is available then more physically based approaches can be used (Ritchie, 1988). There has been work in Queensland to estimate sub-daily intensities from daily totals and this could allow improved runoff estimation (Fraser et al., 2011).

Where the Richards equation is used, the curve number approach is not appropriate, instead a boundary condition must be specified at the soil surface with infiltration calculated by solving the Richards equation subject to this condition, along with details of the soil properties.

The Green-Ampt infiltration approach is provided as an option in 3 models: CREAMS, SWAT, WEPP (Chu, 1978).

A feature of many soils is that they crack when dry so that water can flow down cracks and infiltrate deep within the soil until the cracks seal after wetting. Cracks can also allow the circulation of air and increase the rate of soil drying. These processes can be simulated in some models (e.g., HowLeaky) but not all. APSIM does not currently provide the functionality to allow infiltration via cracks and a study that included infiltration into cracking soils in the Burdekin Delta identified several issues that resulted from this limitation (Stewart et al., 2006). These included:

- Water moves more slowly to deeper levels in the model than in reality
- The model retains water in the root zone for longer than reality and this means there is more water available for plant growth, evaporation and transpiration
- Therefore, the model simulates greater use of water and underestimates deep drainage.

The key message is the need to identify and model the important processes that occur at particular locations. This requires the selection of an applicable model and highlights the need for model builders to provide sub-models and options to meet users' needs.

2.2.1. Curve number approach used in MEDLI

In MEDLI, runoff is calculated using the curve number method. This depends on a retention parameter, S, which is the maximum amount of water that can be retained before runoff commences. The parameter, S is related to a curve number CN, by the relationship:

$$CN = \frac{1000}{(S+10)} \tag{1}$$

This is just a rescaling so that CN is in a convenient range between 0 and 100. The potential maximum retention S increases exponentially as the curve numbers decrease from 100 (Boughton, 1989). In practice curve numbers are usually in the range from 40 to 98 (Ponce and Hawkins, 1996). In MEDLI, the input curve number must be greater than 35.

2.3. Potential evaporation

Potential evapotranspiration (PET) is generally required to be input by the user although was calculated by some models based on other inputs. The most common recommended input was pan evaporation. Others were:

- Penman
- Penman-Monteith

- Priestly-Taylor
- Hargreaves.

When calculating PET, Hargreaves has the least data requirements, followed by Priestly-Taylor (requiring solar radiation and temperature), and Penman-Monteith (daily radiation, wind, dew point temperature and/or relative humidity).

In MEDLI, potential evaporation is estimated from Class A pan data which is required as an input. SILO[1] provides data in a form that can be directly read into MEDLI.

2.4. Erosion and sediment enrichment

If there is an interest in modelling the export of sediment-attached nutrients and pollutants, then it will be important to model erosion and transport of sediment. This capability is available in several models (AGNPS, ANSWERS, APSIM, CREAMS, EPIC, HowLeaky, HSPF, PERFECT, RSULE, WEPP).

Sediment enrichment refers to the preference for nutrients and pollutants to be attached to fine particles, combined with the preferential transport of these fine particles. Thus, the sediment transported from a hillslope can have much higher nutrient content than the average concentration of soil. There is also a correlation between total sediment load and enrichment. If loads are high, then all particle sizes are transported and there is little enrichment. Small loads will consist of mainly fine sediment which can be highly enriched. Thus, management actions to reduce sediment load may not greatly decrease the quantity of exported nutrients because enrichment will increase as loads decrease. Sediment enrichment ratios are referred to as “potency factors” in HSPF.

Another important issue is the routing of sediment across the landscape. Little of the erosion from a hillslope is likely to be delivered to a waterway because it is stored in flatter areas downslope. Sediment can be routed in models such as dSedNet (Freebairn et al., 2015) but this requires 2D capability. The focus of this review was on 1D models where it will be necessary to simulate sediment delivery in a simple way by, for example, using empirical “sediment delivery ratios”.

3. Deep drainage and leaching of nitrate

3.1. Nitrogen processes

The behaviour of nitrogen in the soil is complex. Processes include transport of nitrogen combined with:

- Mineralization which involves the decomposition of plant residues and other organic matter. This releases N into soluble inorganic forms including ammonia and nitrate.
- Immobilization - the conversion of inorganic N into organic compounds which are then not available to plants.
- Nitrification - the conversion of ammonium (NH_4^+) which is less likely to leach from soils, into nitrate ($N0_3^-$) that is more soluble and mobile.
- Volatilization – the loss of, particularly ammonia, into the atmosphere.
- Denitrification - the conversion of nitrate to nitrogen gas which is then lost from soils.
- N fixation – addition of N to soil by legumes.
- Addition of N in waste that is to be treated by land application or in fertilizer, manure, or urine.

These processes are detailed in numerous papers, for example (Misra et al., 1974; Frere et al., 1982; Godwin and Jones, 1991; Stewart et al., 2006).

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[1] https://www.longpaddock.qld.gov.au/silo/

The various processes depend on temperature and other properties of the soil. The processes of mineralization and immobilization depend critically on the carbon/nitrogen ratio. If the C:N ratio is high (greater than about 30:1) N is more likely to be immobilized (Godwin and Jones, 1991).

The behaviour of nitrogen also depends on the type of plants. For example, Anderson et al. (1998), found that there was reduced leaching from pastures in the wheat belt of WA because capeweed (*Arctotheca calendula*) had higher N uptake than wheat or lupin. Similarly, *Carex appressa* has been found to be effective in removing nitrogen in stormwater treatment systems. The characteristics of plants that can achieve high nitrogen removal are those that have large: total root length, root surface area, root mass, root shoot ratio and proportion of fine roots (CRC for Water Sensitive Cities, 2015).

In grazing systems, urine is a major source of nitrogen. The portion of deposited N that is leached depends on the interaction between soils, plants and climate. The risk of leaching is reduced if N can be retained by soil, rainfall is low (so that deep drainage is small) and plants are actively growing (Cichota et al., 2012). This means that leaching risks can be highest at certain times of the year depending on the local climate. For example, Ridley et al. (2001) found that in south-eastern Australia, N accumulated beneath pasture in autumn, when there was less rain, and then leached as nitrate in winter.

3.2. Representation in models

Models vary in their representation of these processes. LEACHM provides a comprehensive approach to modelling N, simulating transformations and flux between 3 different N pools. Processes of mineralisation, nitrification, denitrification, and volatilisation are modelled (Hutson and Wagenet, 1995). Other models that include detailed modelling of N processes are: APSIM, CREAMS, EPIC, HSPF, HYDRUS, OVERSEER, and SWAT.

The detailed modelling of N in APSIM was included in response to the overly simple representation of N processes in CERES. In APSIM, separate pools of N are tracked. Modelled processes include simulation of N inputs from legumes, the changing rate of organic matter decomposition with soil depth, urea hydrolysis, mineralisation (decomposition of crop residues at the soil surface and within the soil), nitrification, and denitrification (Keating et al., 2003; and APSIM online documentation).

For models that include erosion (e.g., CREAMS and EPIC), a key process is the transport of N that is attached to sediment. This requires the use of enrichment ratios to take account of the preferential attachment of N to fine sediment (Palis et al., 1990a; 1990b; 1997). This is important as it affects the nitrogen that is available for runoff.

HowLeaky eschews the complexity of simulating a nitrogen balance and instead requires input of a time series that defines the nitrogen profile in the soil. This could be based on experimental data, expert knowledge, or the results of other models (Queensland Government, 2019).

In HowLeaky, and in most other models, leached N is determined from the simulated concentration of nitrogen in the lowest soil layer combined with the volume of water leaving the soil as deep drainage. Therefore, accurate assessment of deep drainage volumes is critical.

3.3. Deep drainage

Deep drainage occurs when infiltration exceeds soil evaporation, transpiration and soil water holding capacity. This excess water flows below the active soil zone to the water table to add to the ground water.

In the models reviewed for this report, a common way to infer deep drainage is the water that is simulated to drain below the lowest soil profile. This water takes no further part in processes of soil evaporation or transpiration, is effectively lost to the model and is assumed to become deep drainage. The actual behaviour of this water may be complex and there can be substantial uncertainty in deep drainage estimates (Gee and Hillel, 1987).

Application of APSIM to deep drainage below sugarcane in the Burdekin Delta provides a catalogue of challenges (Stewart et al., 2006). Taking account of measurement uncertainties, the estimated error in drainage depth was ±120 m, large compared to the estimated total deep drainage of about 100 mm. Other issues included the inability of the model to simulate processes associated with soil cracking. This means that preferential, rapid flow, to below the root zone would be too low in the model, so the deep drainage would be underestimated.

This study also highlighted the importance of modelling deep drainage as well as upflow from groundwater and the capillary fringe. During the period between planting and the end of February, rainfall was abundant and ET demands were low because the crop was at an early stage of development. Drainage below 1.5 m was 104 mm. Between March and harvest, ET demands were higher, the number of roots had increased and were capable of extracting water at depth. The model simulated upward flow of 161 mm from groundwater to meet crop demands and maintain the capillary fringe. Many of the reviewed models do not include upward flow processes or allow plants to extract water from groundwater.

Deep drainage is also critically dependent on soil type. Similar soils can have substantially different “Partitioning Ratios”, drainage expressed as a proportion of total water loss (sum of surface runoff, subsurface lateral flow and deep drainage) (Ridley et al., 2001). White et al. (2001) proposed a simple model to estimate partitioning ratios based on knowledge of saturated hydraulic conductivity, evaporation and rainfall. Petheram et al. (2002) proposed a function to predict deep drainage based on rainfall alone, but this has low accuracy except in sandy soils.

Gee and Hillel (1988) warn that in arid areas, where PET exceeds rainfall, estimating deep drainage as the residual of a water balance model is likely to have large uncertainties. They recommend using results from lysimeter and tracer studies to calibrate models to local conditions.

3.4. Comparison of models and measurements

There has been extensive research on N leaching (and associated deep drainage). This includes modelling studies that attempt to show the benefits of various management actions, comparisons of models, measurement of nitrogen leaching in the field and comparison of model predictions with measured values. A few of these studies are highlighted below.

Stewart et al. (2006) found that APSIM provided a reasonable estimate of deep drainage and nitrate leaching although with some caveats as noted above. Sharp et al. (2011) compared leaching predictions made by APSIM under intensive cropping, with measured values. They found that APSIM under-predicted annual nitrogen leaching largely because of problems with the way that mineralisation processes were simulated.

Vibart et al. (2015) compared the predictions of APSIM and OVERSEER in relation to leaching of nitrogen from a well-drained soil under a dairy farm. APSIM uses a more sophisticated modelling approach than OVERSEER with greater spatial and temporal resolution but with an increased requirement for user inputs. In the absence of irrigation, long term estimates of leaching were similar from both models. However, APSIM was able to identify that most leaching occurs in winter, but leaching quantities were related to urine deposited in late summer and early autumn. Significant differences were found in the way that irrigation was modelled which influenced drainage estimates and hence nitrogen leaching when irrigation was applied. APSIM was found to be more sensitive than OVERSEER to environmental conditions and management practices.

Work by Asseng et al. (1998) shows the potential value of using models to predict N leaching. Comparison with measured data showed that model predictions were reasonable. The model (APSIM) was used to extrapolate beyond the relatively small range of measured values. The risk of leaching was quantified and changing the timing of fertilizer was shown to both reduce risk and increase crop yields.

3.5. Alternative approaches

The detailed modelling approach of APSIM, LEACHM and other models may be too complex in some situations, especially where there are limited data or were run times must be kept short. Some alternative approaches are available.

A transfer function approach to leaching was developed by Jury et al. (1982) and this has been applied by Cichota et al. (2012) to grazing systems. Cichota et al. (2012) parameterised the output from APSIM as a transfer function and then incorporated this into the simpler OVERSEER model. This retained the user-friendly approach from OVERSEER while making use of the greater detail provided by APSIM. The transfer functions related the number of pore volumes drained, available from OVERSEER model output, to the relative amount of N that is leached. This approach has application to other models that provide a soil water balance.

The Burns equation (Burns, 1976; Scotter et al., 2006) provides another simplified approach. Burns shows that a straightforward equation could be developed to predict leaching if nitrate could be assumed to be uniformly distributed in field soils, or uniformly incorporated to a known depth.

Scotter and Ross (1994) propose a method to estimate local variations in pore water velocity that transport nitrogen. This allows an estimate of the maximum depth that a solute (such as N) can reach in a given time. It can also provide a bound on the maximum amount of dispersion that can occur. There is potential to use this approach to develop transfer functions in a similar way to Cichota et al. (2012) although this would require additional research and development of theory (Cook pers. comm.).

Less applicable is the method of Wagenet and Addiscott (1987) which provides an estimate of the mean and variance of unsaturated soil hydraulic conductivity for a given volumetric soil water content. The required data is unlikely to be available to use this approach (Cook pers. comm.)

4. Influence of cover on soil evaporation

In models that include estimation of a water balance, calculation of soil evaporation is a key component. This requires estimation of a potential rate of evaporation that is then converted to an actual rate by taking account of the available soil moisture. Calculation of the potential rate needs to take account of material that covers or shades the soil surface.

4.1. Approach used in MEDLI

In MEDLI, the potential rate of soil evaporation is reduced if plant material, alive or dead, covers the soil surface. This requires calculation of a factor, TotCover, on each day.

Different approaches are used for:

- Mown pastures
- Crops and continuously resown pastures
- Monthly covers (simple models that have no plant growth or nutrient uptake).

Details are provided in Section 7.4 of the MEDLI manual.

4.2. Approaches in other models

The soil evaporation approach in the 18 models reviewed for this study were examined where relevant documentation could be found. Generally, green cover and plant residue is taken into account to calculate potential soil evaporation with approaches used in all models being reasonably similar.

HowLeaky provides the option of selecting several algorithms including those in PERFECT and there is a thorough explanation of the various approaches. PERFECT uses an estimate of green cover based on leaf area index.

$$\text{Green\_cover} = \text{Min}(\frac{\text{LAI}}{3}, 1) \tag{2}$$

HowLeaky also includes the Robinson[2] method

$$\text{Green\_cover} = 1\text{-}e^{-0.55(\text{LAI}+0.1)} \tag{3}$$

The difference between these two approaches is shown in Figure 1.

In HowLeaky, using the Cover model, the adjustment factor is total_cover x 0.87 which is taken from APSIM.

As well as cover, evaporation is adjusted for residue where the adjustment factor is:

$$e^{\frac{\text{-0.22total\_crop\_residue}}{1000}} \tag{4}$$

Where crop residue is measured in tonnes/ha.

In CEDAR GRASP, the approach is as follows:

$$\text{pot\_soil\_evap} = PET(1 - \text{effective\_surface\_cover}) \tag{5}$$

effective_soil_cover is the proportional effect of total biomass and litter cover on potential soil evaporation.

$$\text{effective\_surface\_cover} = 1 - (1 - \text{trans\_cover})(\text{1-dead\_cover}) \tag{6}$$

trans_cover is the proportional effect of total biomass on reducing soil evaporation.

dead_cover is the proportional effects of standing dead material and litter on reducing soil evaporation

In CREAMS potential daily soil evaporation is calculated from LAI:

$$E_{so} = E_o e^{-0.4\text{LAI}} \tag{7}$$

Where, E_{so} = potential daily soil evaporation, E_o = PET, LAI = Leaf area index.

We can compare the approaches of PERFECT, CREAMS and Robinson (Figure 1). The differences are up to 30% when the LAI is about 3.

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[2] The Robinson method is undocumented but is included as an option in HowLeaky

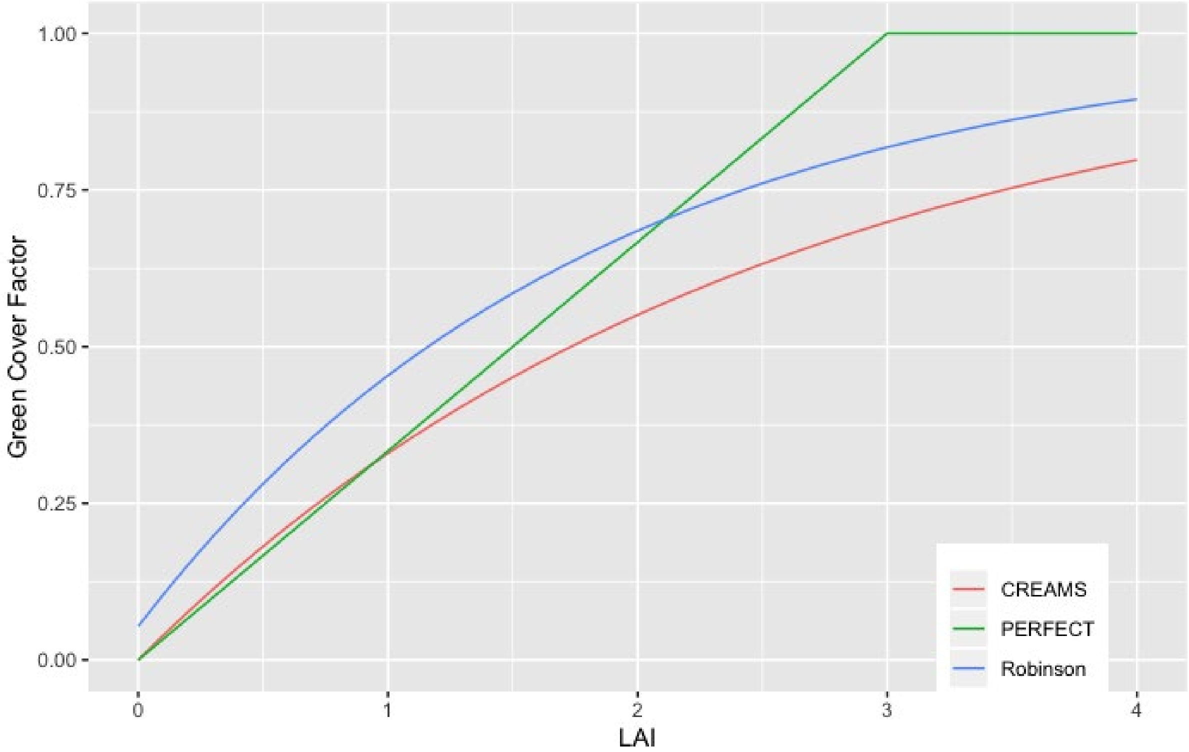

Figure 1 The effect of different algorithms used for converting LAI to green cover factors.

4.3. Literature values

There are several papers that review the effect of cover and/or crop residue on evaporation (Russel, 1940; Todd et al., 1991; Steiner, 1989; Klocke et al., 2009).

The earliest paper (Russel, 1940) suggests the main benefit of residues occurs while the soil is wet with very little reduction in evaporation to a dry soil. Also, the main driver of reduced evaporation is shading so the total quantity of residue is less important than proportion of coverage. The effect of cover also depends on the frequency of rainfall with the greatest benefit occurring when storms are sufficiently close in time that the soil remains wet.

Todd et al. (1991) confirmed Russel’s finding that the greatest effect of residue occurred with wet soil. They found that straw mulch reduced evaporation by 0.1 mm d^{-1} under dryland, 0.5 mm d^{-1} under limited irrigation and 0.9 to 1.1 mm d^{-1} under full irrigation.

Klocke et al. (2009) also found that full coverage of crop residues was required to significantly reduce soil evaporation and that with full coverage, evaporation was reduced by 50% to 65%.

Steiner (1989) related the reduction in evaporation to average residue thickness (mm) (Figure 2). Unfortunately, Steiner (1989) did not consider the proportion of coverage although this will certainly increase as average thickness increases.

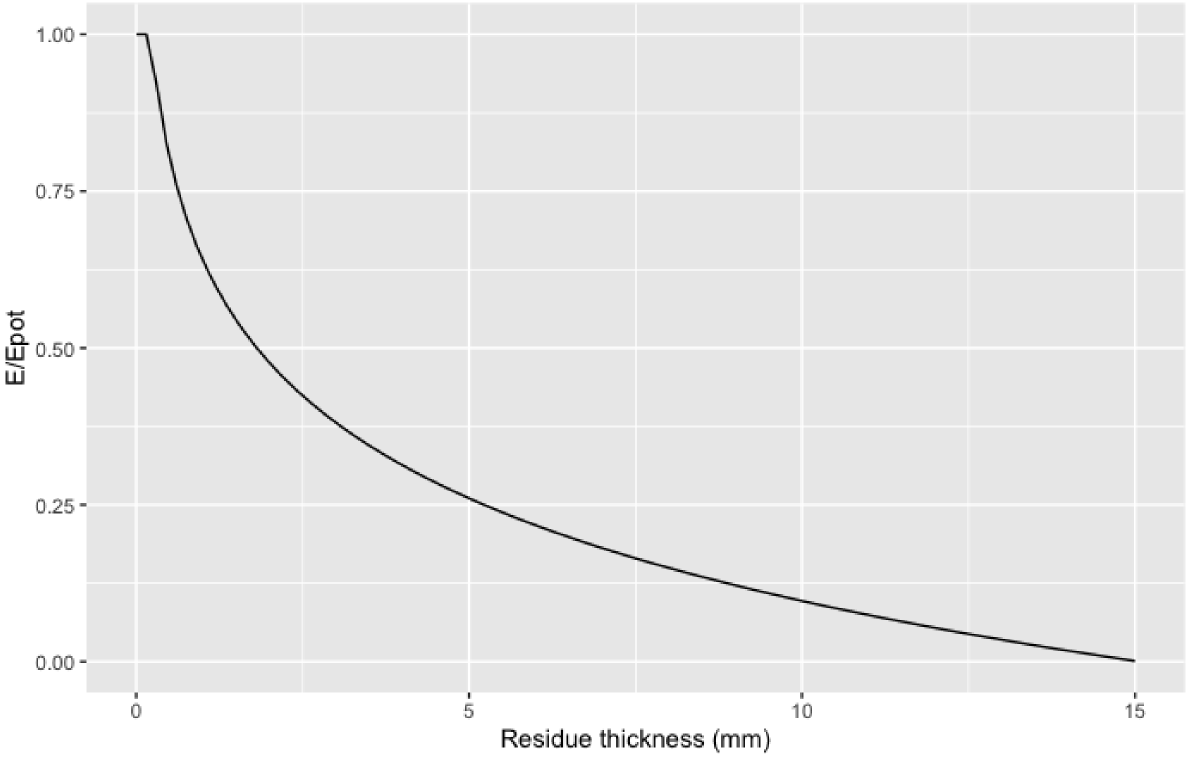

Figure 2 Influence of residue thickness on soil evaporation (Steiner, 1989).

The findings of Russel (1940), Todd et al. (1991) and Klocke et al. (2009) all suggest that the effect of residue cover on evaporation should be non-linear, possibly a logistic growth curve such that there will be limited effect with initial cover, a rapid rise and then a levelling off as cover approaches 100%. Also, the maximum effect should be a reduction to about 50% in E/E_{pot} rather than the 100% implied by Figure 1. A possible example curve is shown in Figure 3. This contrasts to the equations shown in Figure 1 which are either linear or concave downwards. There may be sufficient information in the various studies to fit such a curve which could then be included in models.

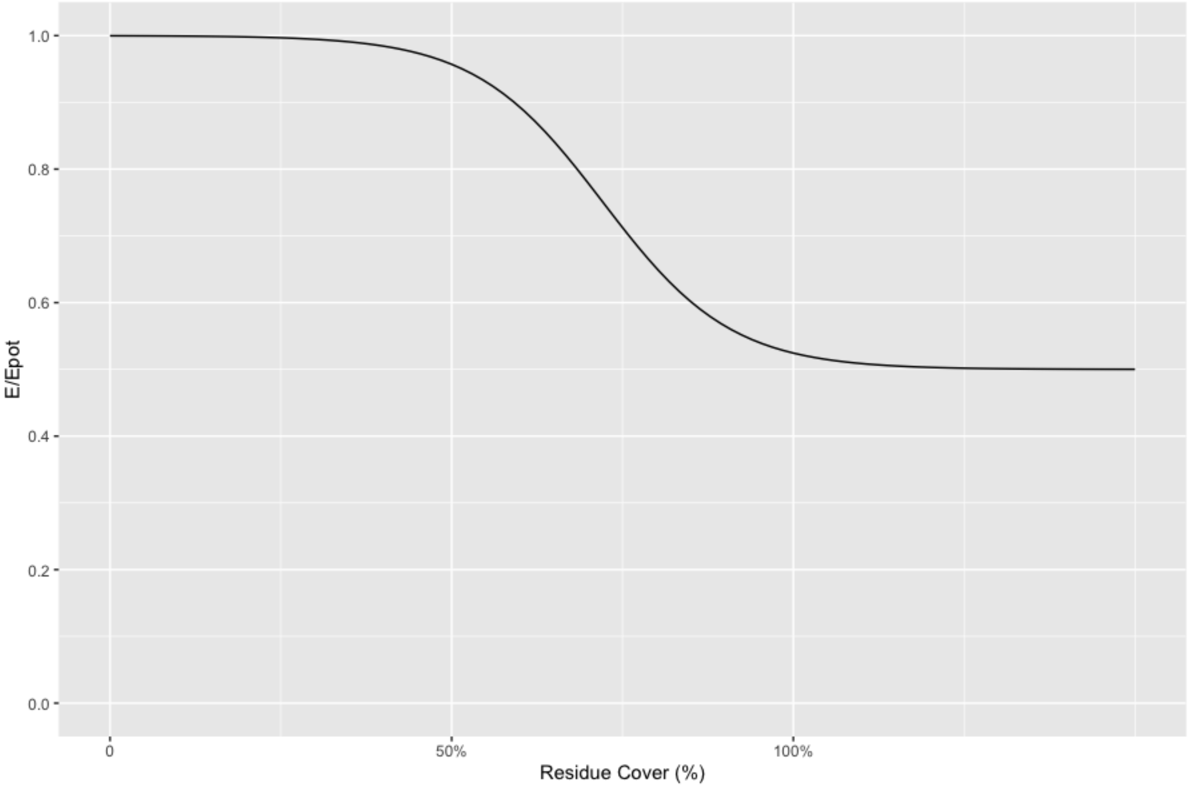

Figure 3 A conceptual response surface showing the effect of residual soil cover on potential soil evaporation.

Note that there is no advantage in having very large amounts of residue. As the amount of crop residue increases rainfall interception increases so although evaporation may be reduced, the amount of water reaching the soil is also decreased (Bussiere and Cellier, 1994). There is likely to be some optimum level of cover, probably near to where the entire surface is covered in a thin layer of residue.

5. Implications of the issues identified

Implications of the issues identified in this report for MEDLI are summarised in Table 1.

Table 1 Strategic overview of the issues and implications for MEDLI raised by this review of 18 hydrologic models, with additional insights from the Synthesis Report (Gardner 2021).

Model Process	**Issue(s) identified**	**Current handling**	**Proposed alternative(s)**	**Implications**	**Degree of difficulty**	**Importance**	**Recommendation**
Infiltration /runoff	The infiltration/runoff module uses SCS Curve number (CN) approach which is a well-tested infiltration model for dryland soils but not irrigated soils.	Curve Number (CN) approach is used in MEDLI and in 9 of the models reviewed. It assumes that there is a maximum amount of water that can be retained ("S" mm) by the soil before runoff commences. CN is scaled to 100 when S = 0 and falls towards 35 as S increases. Only daily rainfall data is required plus adjustment to CN for soil texture and stubble cover.	Alternative infiltration models suggested are the Green-Ampt infiltration model and the fundamental Richards equation. Green-Ampt has the ability to consider sub daily time steps, without the cost of needing lots of new soil input parameters. But its solution for time varying rainfall is complex. (Cook 2021 discusses this in more detail).	Both equations require more complex soil hydraulic properties than CN and more complex numerical solutions. APSIM provides a relatively simple method to obtain the soil water hydraulic properties needed for the Richards equation (see Huth et al. 2012)	Potentially high. Cook 2021 has provided a methodology to solve the Green-Ampt implicit equation for variable rainfall rates.	Infiltration is critically important in hydrology models as it determines recharge of the soil water deficit.	Investigate inclusion of this code. Use a similar experimental protocol as that used for dryland paddocks in Queensland.
Transpiration	The use of Class A pan is being phased out by BOM in favour of Penman-Monteith equation. FAO 56 no longer recommends Class A pan.	MEDLI uses Class A pan data provided directly from the SILO Australian climate data base (which is taken from BOM).	1) Potential evapotranspiration (PET) can be estimated using the more physically rigorous Penman, Penman-Monteith, and Priestly-Taylor equations. 2) Continue to use Class A Pan in MEDLI by using SILO website synthetic pan data.	1) Testing would be needed to compare Class A Pan data with Penman-Monteith data from SILO. This should be followed by testing MEDLI outputs using paired Class A pan and PM data. Note that the crop coefficients will change between models to deliver the same Transpiration for a given climate data set. 2) No change	Tedious testing but not particularly computationally difficult.	Errors in Evapotranspiration will spill over to errors in the whole water balance, especially under irrigated conditions. Important that Penman-Monteith does not generate different water balance (to Class A pan) on test data sets.	Class A pan should be retained as the potential to get non-corresponding results is quite high. This in turn will require extensive fine tuning of MEDLI algorithms. SILO is handling the phasing out of Class A pan data by generating synthetic pan values from BOM weather data.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
Effect of crop residue and cover on soil evaporation	Green and dead cover are assumed to have the same effect on reducing potential soil evaporation. Experimental data shows that dead biomass (kg/ha) is much more important in reducing evaporation than % dead cover.	The proportion of soil that has green (transpiring) cover is assumed to have no soil evaporation. The same assumption applies to dead surface cover (e.g., mulch) as it makes no allowance for the thickness or mass. That is, a 1 mm thickness of dead cover is assumed to be as effective in reducing evaporation as a 10 mm thickness, for equal soil cover %s	Adopt the HowLeaky evaporation algorithm which explicitly considers residue mass on evaporation reduction. This is much more physically realistic.	Simple change.	Low	Underestimating soil evaporation due to complete, but thin, dead cover can translate into underestimating Irrigation Demand by up to 100 mm/yr. in SEQ	Adopt HowLeaky dead cover algorithm in MEDLI
Soil Evaporation	None.	Bare soil evaporation is predicted using Richie's 2-stage soil evaporation algorithm. Stage I involves demand-driven soil evaporation at the potential evaporation rate. Stage II is supply driven, and evaporation continues much more slowly. Its rate is estimated as a function of the square-root of time since rainfall.	None. No action to be taken.	None. Evaporation has been well studied in Queensland by Jenny Foley so no need for more of this technically difficult experimentation	Not applicable.	Not applicable.	Retain Ritchie's soil evaporation algorithm.
Erosion and sediment enrichment	Erosion and sediment enrichment is not currently modelled in MEDLI. But it is considered in model such as HowLeaky and APSIM.	Erosion and sediment enrichment is not modelled in MEDLI.	Consider inclusion of Enrichment Ratio as per HowLeaky.	Implementation would allow nutrient enrichment in runoff to be predicted	Potential high, especially since mass balance considerations will need to be addressed.	Low Erosion is unlikely to be an issue in pasture dominant irrigated effluent disposal	Review options for inclusion.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
Loss of N & P in surface runoff	Surface runoff will export DIN (dissolved inorganic nitrogen) and ortho-phosphate.	None.	For nitrogen, use N loss algorithm from HowLeaky and GRASP. For phosphorus, use the P loss in runoff algorithm described in Moody 2021).	Mass flux of dissolved N & P likely to be small except when rainfall runoff shortly follows effluent irrigation. However, concentrations could exceed ANZECC standards.	Moderate.	Moderate.	Incorporate these two-simple algorithms into MEDLI.
Redistribution of soil water down the profile / Drainage	1)Drainage module is empirical but can give the correct time trend of soil drainage. However, Cook (2021) argues that the shape of the draining soil water profile is incorrect. The issue needs more desktop investigation. 2) Excessive deep drainage **may** occur on the first irrigation of the cropping season if shrinkage cracks link up with permanent deep sub soil structural cracks (slickensides). Soil physics theory cannot predict this behaviour. A review of deep drainage literature (e.g., research in southern QLD and NSW by Silburn, Montgomery and others) may show if the first irrigation of the season leads to infiltration	A 1-dimensional cascading bucket model moves water in excess of "Field Capacity" downward through the soil profile, modified by the saturated hydraulic conductivity of each defined "soil layer". The algorithm reproduces the expected non-linear reduction in drainage rate with elapsed time.	1) The Richards equation is a more sophisticated approach, and only used by one of the reviewed models (APSIM-SWIM). Cook (2021) suggests the Sisson model will better capture both the time trend of drainage rate and the shape of the soil water profile for a modest increase in data inputs & computational complexity.	Deep drainage and solute leaching are important outputs of the MEDLI model. They need to be as correct as practically possible. It's possible the incorrect soil moisture profile shape will affect solute leaching predictions	Moderate.	1) Very important. Upgrading the drainage algorithm in MEDLI is considered to be of high priority. (2) No relevance to effluent irrigated pasture	Investigate inclusion through further post-graduate research.

Model Process	Issue(s) identified	Current handling	Proposed alternative(s)	Implications	Degree of difficulty	Importance	Recommendation
	far exceeding soil water deficit.						
Upflow	No consideration of upflow from a groundwater table nor from a wetter subsoil relative to soil surface moisture content.	Deep drainage is predicted using a one-dimensional cascading bucket model.	Consider the approach used in APSIM using a simple Diffusivity parameter and a water content gradient.	Potentially not too much extra complexity but need investigation.	Potentially difficult	Only relevant for irrigated soils with a water table < 1 .5 m deep.	No further action.
Leaching of nitrate	Leaching of solutes (nitrate) done too simplistically in MEDLI. Differential solute movement through the soil pores (of different diameters) and lateral flows are not considered.	N leaching calculated from predicted deep drainage and the predicted nitrate-N concentration in the lowest soil layer. Lateral flow of water and nitrate is ignored.	(1) A simple convective one-dimensional flow model adjusted for mobile soil water content, deep drainage below the root zone and **mass** of nitrate above the root zone as per Burns 1975, Corwin et al. 1991 and Scotter et al. 1993. (2) A Transfer Function approach can capture the variation in solute velocity between soil pores which cause a diffuse solute front similar to that observed and predicted by convective-dispersion (CD) theory, but without the computational complexity of the CD equation. But this requires calibration with another solute leaching data set.	(1) The key insight is the need to define the **mobile water fraction** that moves most of the nitrate via convective flow. More detail on concentrations by soil depth and time can be obtained by the Scotter et al.'s 1993 improvement of the Burns model. Adding these concepts to MEDLI could be done relatively easily. (2) Transfer Function models has no future in MEDLI Lateral flow is too complex for most users of MEDLI. But lateral flow is more likely to occur in sloping Duplex soils in winter dominant rainfall where Rain >> ET for months.	(1) Easy but need to estimate mobile water as a fraction of the DUL moisture content. (2) High.	(1) High importance as nitrate leaching a key MEDLI output. (2) Low except in southern Australia where Rain >> ET for months.	The drainage algorithm (based on cascading buckets) needs improvement as per the Cook (2021) review.

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Appendix A: Model review

A summary of the capability of 18 models is provided in Table A1 below. There are 25 columns of data in total which are laid out across four tables.

Table A2 Summary of modelling approaches

No	Model	Full Name	Brief description	Infiltration/Runoff	Curve number soil water deficit	Temporal modelling approach	Time step	Spatial scale
1	AGNPS	Agricultural Non-Point Source.	Analyse nonpoint-source pollution and prioritise water quality problems. Runoff, sediment, nutrients, and chemical oxygen demand are simulated for each cell and routed to the outlet.	Curve number (event based). Peak flow rate calculated as in CREAMS	Curve number based on land use, soil type and soil moisture. (Curve number is a model input. There is no soil moisture accounting)	Event based	1 minute	Watershed scale. Distributed. 2D (grid) cell size 0.4 to 16 ha.
2	ANSWERS	Areal Nonpoint Source Watershed Environmental Simulation	Model the quality and quantity of water and the effect of management interventions	Interception and surface ponding are removed from rainfall. Infiltration is modelled as a function of soil moisture. Runoff is any unaccounted-for rainfall	Does not use curve numbers	Event based	1 minute	Model size from a few ha to 300,000 ha"
3	APSIM	Agricultural Production System Simulator	Simulates biophysical processes in farming systems with a focus on the influence of climate risk on economic and ecological outcomes to management interventions.	Two options. 1. Curve number approach as in CREAMS, PERFECT etc. (No runoff is assumed from irrigation applications). 2. Rainfall/evaporation at the soil surface specified as a boundary condition to the Richards equation	1. As in PERFECT i.e., current soil water content effects the *s* parameter. 2. As per SWIM i.e., specification of boundary conditions, soil roughness and the way roughness changes through time and with cumulative rainfall	Continuous	SOILWAT uses a daily time step. SWIM uses an adaptive time	Distributed (square grid over a landscape). Small watershed scale i.e., larger than field scale
4	CERES	Crop Estimation through Resource and Environment Synthesis	Model purpose is to provide: - Assistance with farm decision making - Risk analysis for strategic planning - Within-year management decisions - Large area yield forecasting both foreign and domestic - Policy analysis - Definition of research needs	Infiltration is the difference between daily precipitation and runoff. Runoff is calculated using a modified SCS-Curve number approach (similar to other models) (Williams et al., 1991). All irrigation is assumed to infiltrate	Similar to EPIC ie. *s* (retention parameter) is a function of soil water content as a fraction of available water (field capacity - wilting point). Relationship takes account of the distribution of water in the soil profile	Run for any length of time before the crop sowing date, then for the growing season of the crop.	Daily	1D model, Field scale

No	Model	Full Name	Brief description	Infiltration/Runoff	Curve number soil water deficit	Temporal modelling approach	Time step	Spatial scale
5	CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems	CREAMS is a physically based, daily simulation model that estimates runoff, erosion, and sediment transport, to determine the yield of plant nutrients and pesticide, and sediment from field-sized areas.	Two options. 1. When daily rainfall is available, runoff is estimated using a curve number approach. (Williams and LaSeur, 1976) 2. If sub-daily data are available, an infiltration model (based on Green and Ampt) is used. Uses an empirical equation to predict peak runoff based on runoff volume, catchment area, channel slope, and length-width ratio. Irrigation was added to CREAMS in 1983 (Del Vecchio et al., 1983).	Depth averaged retention parameter based on weighing of soil moisture in 7 soil layers. Soil moisture is characterized as ratio of actual/upper limit. Weighting factors are a function of the ratio of soil depth to root zone depth.	Continuous	Daily time step for evaporation and soil water movement between storms and shorter time increments, depending on available rainfall records, during storms	Field scale (1D) Management unit having 1. Single land use 2. Relatively homogeneous soils 3. Spatially uniform rainfall 4. Single management practices. Mixed land uses are subdivided, predictions are made for each sub-area and then combined,
6	EPIC	Erosion Productivity Impact Calculator	EPIC simulates erosion and plant growth to determine the effect of erosion on yield. Includes economic assessments	Curve number to calculate runoff volume. Rational method to calculate peak flow (stochastic approach used to estimate sub-daily peaks)	*s* (retention parameter) is a function of soil water content as a fraction of available water (field capacity - wilting point). Relationship takes account of the distribution of water in the soil profile	Continuous. Capable of simulating 100s of years	Daily	1 ha area, up to 10 soil layers
7	GLEAMS	Groundwater Loading Effects of Agricultural Management Systems	Model developed for field-size areas to evaluate the effects of agricultural management systems on the movement of agricultural chemicals within and through the plant root zone	Curve number approach as in CREAMS	Same as CREAMS	Continuous	Daily	Field scale (see description for CREAMS)
8	GRASP	Grass Production	Model of climate-soil-plant-animal-management of pastures in northern Australia	Rainfall is partitioned into infiltration and runoff on the basis of surface cover, rainfall intensity and soil water deficit (Scanlon et al., 1996). Sub-daily rainfall intensity is derived from daily rainfall. Does not model infiltration in cracking soils	Not used	Continuous. Some procedures are calculated annually, e.g., pasture burning	Daily	1D model representing a point in the landscape. Has been adapted to 2D in programs such as AussieGRASS

No	Model	Full Name	Brief description	Infiltration/Runoff	Curve number soil water deficit	Temporal modelling approach	Time step	Spatial scale
9	HowLeaky		Designed to assess the impacts of different land uses, soil conditions, management practices and climate types on water balances and water quality	Curve number based. Infiltration is water left over after runoff. Can model infiltration into cracking soils.	Effective rain = rainfall plus un-infiltrated irrigation CN_2(bare) = curve number (rainfall v runoff response) for average antecedent moisture conditions and for bare and untilled soils. CN_2 is modified to account for crop cover, surface residue cover and surface roughness. Applied CN is a function of soil water deficit and Smax (maximum retention under dry antecedent conditions). Allows modified approach to calculating Smax (Robinson 2011)	Continuous	Daily	Field scale (1D)
10	HSPF	Hydrologic Simulation Program Fortran	Watershed hydrology and water quality model for conventional and toxic organic pollution. Can model pervious and impervious areas. Models waterway and hillslope processes. HSPF is based on a set of modules in a hierarchical structure.	Precipitation is supplied by the user which can then be intercepted by vegetation and detained on the surface. Remainder is partitioned between runoff, infiltration, interflow and remaining in storage	not used	Continuous (few min to > 100 years)	Sub-hourly to daily time step. Commonly hourly.	Watershed scale. A few ha to large watersheds (160,000 km2). Catchments are divided into areas providing homogeneous hydrologic and water quality response. Models streamflow as well as hillslope processes
11	HYDRUS-1D		Software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media	Can model ponding at the soil surface with or without runoff. Behaviour at top and bottom boundaries is specified as boundary conditions. Dirichlet boundary condition - ponded infiltration (1D vertical water flow). Neuman boundary condition - specification of flux of water entering or leaving a system. Atmospheric boundary condition require specification of precip and evaporation	Not used	"Daily variations in evaporation, transpiration and precipitation rates". Meteorological variables can be generated	Adaptive time step depending on the speed of convergence	1D, field scale

No	Model	Full Name	Brief description	Infiltration/Runoff	Curve number soil water deficit	Temporal modelling approach	Time step	Spatial scale
12	LEACHM	Leaching Estimation And Chemistry Model	Process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone	Specification of the upper boundary condition determines the partition between runoff and infiltration	Not used	Intended for use during a growing season	Adaptive time step depending on the speed of convergence	1D, field scale
13	OVERSEER		OVERSEER is a strategic management tool that supports optimal nutrient use on form for increased profitability and managing within environmental limits. Simulates off-farm losses of nutrients and greenhouse gases	Daily rainfall greater than a threshold amount generates runoff, the remainder infiltrates. Threshold rainfall is a function of soil moisture (variable), and clay content, slope and a drainage factor. Wheeler, 2018a	Does not use curve numbers	- 2-year modelling period for pastoral, cut and carry and fruit. - 3-year cycle for crops	Daily time step for the hydrology model. Monthly loads for N, annual loads for other nutrients	Paddock or farm scale (1D)
14	PERFECT	Productivity Erosion Runoff Functions to Evaluate Conservation Techniques	PERFECT is a biophysical model that simulates the plant soil water management dynamics in an agricultural system to predict runoff, soil loss, soil water, drainage, crop growth and yield	Curve number based. Infiltration is water left over after runoff. Can model infiltration into cracking soils.	CN_2(bare) = curve number (rainfall v runoff response) for average antecedent moisture conditions and for bare and untilled soils. CN_2(bare) is modified for the effects of cover and roughness (which is a function of tillage type and rainfall since tillage). The *S* parameter is modified based on soil water content.	Continuous	Daily time step	Field scale (1D)
15	RUSLE	Revised Universal Soil Loss Equation	The RUSLE is an erosion model predicting long time average annual soil loss resulting from raindrop splash and runoff	Not used	Not used	Lumped	Annual average	Field scale (1D)

No	Model	Full Name	Brief description	Infiltration/Runoff	Curve number soil water deficit	Temporal modelling approach	Time step	Spatial scale
16	SWAT	Soil and Water Assessment Tool	Predict the effects of alternative land use management practice on water, sediment, crop growth, nutrient cycling, and pesticides	SCS-Curve number or Green & Ampt to determine runoff volume. Rational formula or TR-55 to determine peak flow rate.	*s*, the retention parameter, is a function of soil moisture (fraction of field capacity)	Continuous	Usually daily but can use sub-daily to yearly time step (Yuan et al., 2020; Borah & Bera, 2003).	Small watersheds (10 km^2) to continental scale (Europe). Catchments are divided into sub-basins and into Hydrological Response Units (HRUs). HRUs are homogeneous in terms of land use, soils and topography.
17	SWIM	Soil Water Infiltration and Movement	Simulates runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage and leaching	Rainfall and/or irrigation provided as inputs. Infiltration behaviour is specified as a boundary condition. Commonly runoff is an empirical function of ponding depth. Can model sealing and crusting soils and their time dependence	Not used	Continuous	Adaptive time step. Small stepping during conditions of rapid change. SWIM will linearly interpolate cumulative climate inputs e.g., PET and rainfall.	Can be used at very small scales e.g., laboratory columns. Can be used at management scales as part of APSIM
18	WEPP	Water Erosion Prediction Project	Continuous simulation program to predict soil loss and sediment deposition from overland flow on hill slopes and concentrated flow in small channels	Interception by vegetation is related to above ground biomass. Infiltration estimated by modified Green-Ampt Mein-Larson model (Chu, 1978) which takes, as an input, soil moisture from the upper soil layer.	Curve number is not used	Continuous	Time step depends on the module. Hydraulic calculations use an adaptive time step. WEPP uses stochastically generated weather data, so the time step is not constrained by observational data	Tens of metres for hillslope profiles and hundreds of metres for small watersheds. Uses overland flow elements (OFE) which have homogeneous properties and a uniform response.

Table A1 Summary of modelling approaches (continued)

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
1	AGNPS	Not used	Not modelled	Not modelled	Not modelled	Not modelled	Models Nonpoint sediment sources and can include point sources (gullies, feedlots) Soil loss calculated using a modification of the USLE. Sediment is routed between cells. Transport capacity based on flow velocity and shear stress. Uses 5 particle sizes: clay, silt, small aggregates, large aggregates and sand.	Enrichment ratio based on sediment yield and soil texture
2	ANSWERS	Not used	Not modelled	Subsurface drainage only occurs when soil water content is greater than field capacity. Tracking soil water distribution is not a focus of this event model.	Not modelled	Not modelled	Modification of the USLE to include rill and inter-rill (a) rainfall detachment (Meyer and Wishmeier, 1969), and (b) overland flow detachment (Foster, 1976). Rate of sediment movement is a function of rainfall detachment, flow detachment, and available transport capacity of overland flow. Channel erosion is assumed to be negligible, but channel deposition is modelled.	Not modelled
3	APSIM	Priestly-Taylor or Penman-Monteith	1. Ritchie two stage model, including effect of surface residue and crop cover on runoff and potential evaporation. 2. Evaporation demand as a boundary condition when solving the Richards equation	Two submodels, SOILWAT and APSIM-SWIM. SOILWAT is a cascading soil layer model (up to 10 layers) similar to that in CERES and PERFECT. Can model perched water tables and unsaturated flow. APSIM-SWIM is based on the numerical solution to the Richards Equation (see the description of SWIM)	The transpiration approach is not well explained in documentation but likely that SOILWAT uses similar routines to PERFECT In SWIM, transpiration is modelled by root exploration and extraction potential	1. As in PERFECT 2. Root demand as a sink term in Richards equation	Erosion modelling combines sediment concentration with runoff volume calculated by the SOILWAT module and takes account of surface residue from crop modules and/or the RESIDUE module. There are two options for obtaining sediment concentration: 1. The approach developed by Rose (1985)	Empirical, power function, based on the total soil loss (t/ha)

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
							which allows separate calculation of bed and suspended load. 2. A modification of the USLE to calculate daily sediment concentration rather than annual soil loss. A similar approach was used in PERFECT	
4	CERES	Priestley-Taylor (1972)	Ritchie (1972) model. Soil evaporation potential rate is PET modified by LAI. Two stage evap. Stage 1 at potential rate until the cumulative evaporation exceeds U (the upper limit of stage 1 drying). Stage 2 at CONA. Modification of Ritchie (1972) to reduce soil evaporation when the soil water content in the upper soil layer reaches a low threshold. Evaporation can remove soil to air dry, assumed to be half the lower limit (LL) of the upper layer. (LL is -15 bar water content) (Ritchie, 1998)	Soils modelled as a series of 7 to 10 layers, 200 to 300 mm deep. Drainage is a function of the water content above the drained upper limit (DUL). Drainage coefficient is the fraction of water (between DUL and field saturation) that can drain on each day. A single drainage coefficient is specified for the entire profile. Upward flow of water in the top 4 soil layers is calculated based on soil evaporation. Soil water can move by diffusion (Rose, 1968)	Transpiration is the minimum of the potential rate, or a rate calculated from the capacity of the root system	Root water uptake (and hence transpiration) is reduced to zero when soil water reduces to the soil lower limit (-15 bar).	Not modelled	Not modelled
5	CREAMS	Priestley-Taylor (1972)	Ritchie (1972) model. Soil evaporation potential rate is PET modified by LAI. Two stage evaporation to defined wilting point Stage 1 at potential rate) until the cumulative evaporation exceeds U (the upper limit of stage 1 drying). Stage 2 at CONA No decrease in stage 2 rate as soil dries.	Soil movement between layers. Drainage occurs when soil water content is greater than field capacity. The amount of drainage is a function of Ksat and the difference between current soil water content and field capacity. The capacity for the next soil layer to hold the drained water is also considered. Unsaturated water flow is ignored	Potential transpiration = PET adjusted for LAI if LAI is < 3.	Actual transpiration is reduced below potential when soil water storages is less than 25% of field capacity. Transpiration continues down to soil water content of -15 bar (wilting point). Water demand by vegetation varies by soil depth.	USLE plus sediment transport capacity of overland flow, channel erosion and deposition and storage of sediment in dams	Enrichment ratio based on an empirical relationship with sediment load. Er = A(SED)^B SED = kg/ha of sediment A = 7.4 B = 0.2
6	EPIC	Priestly-Taylor (1972) or	Potential soil evaporation = PET adjusted for LAI. Actual evaporation	Storage routing approach to modelling soil percolation.	Potential transpiration = PET adjusted for LAI if	Actual transpiration is reduced below	Water erosion based on USLE (Three versions of	Sediment enrichment ratio is a function of the

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
		Penman. Later version used Penman-Monteith (Mearns et al., 1999)	calculated from exponential functions of soil depth and water content.	Flow from a soil layer occurs when soil water content exceeds field capacity. Movement is limited by the available capacity of the lower soil layer. Models lateral flow	LAI is < 3. Transpiration demand is distributed between soil layers	potential when soil water storages is less than 25% of plant available water. Exponential reduction to ~0 when soil dries to wilting point (Jones and Kiniry, 1986)	USLE are offered). Also simulates wind erosion.	sediment delivery ratio (DR). DR is estimated from the ratio of peak runoff rate and peak rainfall excess rate. Sediment enrichment ratio varies logarithmically between 1 and 1/DR. Sediment enrichment ratio approaches 1 for high sediment concentrations
7	GLEAMS	Same as CREAMS	Same as CREAMS	Seven computational soil layers. Soil properties can vary by layer. Storage-routing technique used to simulate layer-to-layer percolation is the same as CREAMS	Same as CREAMS	Same as CREAMS	Improvement in calculation of sediment particle characteristics compared to CREAMS (Foster et al., 1985)	Similar to CREAMS but with improved estimates based on changes to parameterization of sediment particle characteristics of detached soil
8	GRASP	Pan	Transpiration is calculated first then soil evap. Total evapotranspiration cannot exceed potential. Soil evaporation is based on a potential rate (pan), adjusted for soil cover and tree density. Actual soil evaporation is potential adjusted for available water	Based on an updated version of the WATSUP soil water balance model (Rickert and McKeon, 1982; McKeon et al., 1982). Soil water updated daily on the basis of infiltration and drainage when a soil layer is above field capacity. Three layers plus a 4th below 100 cm which is only available for trees. All water above field capacity is drained from each layer to the layer below in one day. Does not model run-on, lateral drainage, upward movement of soil moisture, or unsaturated flow.	Separate calculation of transpiration from grass and trees. Trees remove water first. Actual transpiration based on potential rate adjusted for available water. Wilting point is a property of vegetation rather than soil. GRASP does not simulate root growth	Transpiration is a function of the ratio of available soil moisture (actual soil water - wilting point soil water) to capacity (field capacity - wilting point)	Not modelled	Not modelled
9	HowLeaky	Pan	Ritchie Two stage evap to defined wilting point Stage 1 at potential rate (modified by crop residue) until the cumulative	Cascading bucket (similar to PERFACT and CREAMS)	Potential rate: PET x green cover, or PET x LAI Also includes a simple Crop-factor model that	Function of soil water for each layer. Based on the ratio of plant	Modified USLE function of: runoff volume cover soil erodibility	Empirical functions for calculating enrichment of total P in sediment and concentration of soluble P in runoff.

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
			evaporation exceeds U (the upper limit of stage 1 drying). Stage 2 at CONA No decrease in stage 2 rate as soil dries. Potential soil evaporation is a function of green cover and/or crop cover. Section 1.6 states that potential soil evaporation is based on unsatisfied evaporative demand i.e., difference between potential evapotranspiration and transpiration. However, Section 4.1 suggests it is potential transpiration that is based on unsatisfied evaporative demand. That is, it is not clear which if soil evaporation, or transpiration is calculated first		lumps evaporation and transpiration into a single evapotranspiration output. Potential rate is based on unsatisfied evaporative demand i.e., difference between potential evapotranspiration and soil evaporation.	available water and drained upper limit.	management practice topography	Uses Phosphorus buffering index test (PBI) to modify soil P concentration in runoff
10	HSPF	Input by user. Typically Pan values are used with an adjustment factor	Potential rate is adjusted for cover and soil moisture (ratio of available to max available)	Interflow outflow, percolation, and groundwater outflow using empirical relations. Based on the LANDS subprogram of the Stanford Watershed Model	Potential rate adjusted for vegetation type, depth of rooting, density of vegetation cover, stage of plant growth and moisture characteristics	Depends on ratio of actual available soil moisture to max available soil moisture	Rainfall splash detachment and wash off. Transport capacity is a function of water storage and outflow. Scour based on stream power (Borah & Bera, 2003)	Referred to as "potency" factors. Separate user supplied factors are required for washed off sediment and scoured sediment
11	HYDRUS-1D	Penman-Monteith or Hargreaves equations	Evaporative demand is set as a boundary condition at the soil surface	Numerical solution of Richards Equation for variably saturated water flow and the advection-dispersion equations for heat and solute transport. Can take account of matric and macropore flow and model vapour transport. Flow and transport can occur in the vertical, horizontal any other direction	Transpiration is modelled by root water uptake which is specified as a sink term in the differential equations	Sink term as part of the Richards equation to model water uptake by roots	Not modelled	Not modelled

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
12	LEACHM	PET input by the user as weekly totals	PET partitioned into potential transpiration and potential soil evaporation based on the crop cover fraction.	Finite difference solution to Richards equation	Calculated as a sink term that is a function of hydraulic conductivity, effective crown water potential, root resistance, soil water matric potential, fraction of active roots in the depth segment	Richards equations with root uptake as a sink term	Not modelled	Not modelled
13	OVERSEER	PET required as an input, documentation doesn't specify any specific requirements	Soil evaporation (and transpiration) is set to zero when soil moisture reaches wilting point. PET is allocated between soil evaporation and transpiration depending on vegetation cover.	Calculations use 100 mm soil layers. Profile depth is 600 mm for pastoral blocks and 1500 mm for Lucerne and crops	Transpiration = PET x cover x dryness cover = monthly crop cover (0,1) dryness approaches zero as profile soil water content approaches wilting point.	Transpiration (and soil evaporation) is set to zero when soil moisture reaches wilting point.	Not modelled	Not modelled
14	PERFECT	Pan	Two stage evaporation. Drying is initially at potential rate to a user defined limited. Followed by slower stage 2 drying. Evaporation will remove soil water from the two upper profile layers and drying continues below wilting point to the user specified air dry limit (layer 1) and in layer 2 to halfway between wilting point and the air dry limit. Stage 1 drying recommences after infiltration but is limited be amount of infiltration. This differs from the original Ritchie (1972) algorithm. Potential rate is based on Pan adjusted using a function that depends on crop cover, LAI and crop residue.	Cascading bucket (similar to CREAMS)	Based on potential, allocated to each soil layer and then adjusted for the available soil moisture in each layer	Transpiration can only dry a profile layer to its defined wilting point	Modified USLE function of: runoff volume cover soil erodibility management practice topography. Uses a modified LS (length slope) factor from the RUSLE (Freebairn and Wockner, 1986). Calculates daily sediment concentration rather than annual sediment load. Also models the impact of soil erosion on crop yield (Littleboy et al., 1992)	Not used
15	RUSLE	Not used	Not used	Not used	Not used	Not used	Annual average soil loss is a function of the same six factors as the USLE but based on more data, better computational	Not used

No	Model	Potential ET	Soil evaporation	Soil water redistribution	Transpiration	Transpiration-soil water storage relationship	Erosion	Sediment enrichment
							procedures, and more sophisticated relationships.	
16	SWAT	Hargreaves, Priestley-Taylor or Penman-Monteith	Uses the method of Ritchie (1972)	Lateral subsurface flow using kinematic storage model (Sloan et al., 1983), and groundwater flow using empirical relations.	Potential ET is a linear function of potential ET and leaf area index. Actual ET depends on available soil moisture	Rate depends on the fraction of field capacity down to wilting point.	Modified USLE (Williams and Berndt (1976). Sediment yield expressed in terms of runoff volume, peak flow and USLE factors.	Uses a sediment enrichment ratio as part of the calculation of N and P export
17	SWIM	Evaporative demand needs to be supplied by the user. This becomes a sink term when solving the Richards eqn.	Soil evaporation is a sink term when solving the Richards eqn. Uses the method of Campbell (1985). Evaporation is a function of the relative humidity of the atmosphere and the relative humidity at the soil surface which is a function of its water content.	Numerical solution of Richards Equation and the advection-dispersion equation. Flow is one dimensional. Lateral flow is not calculated	The PET supplied by the user must incorporate the effect of stomatal and aerodynamic resistance. SWIM can model transpiration from 4 vegetation types. Vegetation is behaviour is assumed fixed and known in advance as SWIM does not model plant growth	Actual transpiration rate depends on soils ability to supply water as determined by the solution to the Richards equation	Not modelled	Not modelled
18	WEPP	Penman (Penman, 1963; Jensen, 1974) where data are available (daily radiation, temp, wind, dew point temp or relative humidity). Priestly-Taylor (1972) when only solar radiation and temperature data are available.	Potential soil Evaporation is a function of potential ET and LAI. Uses the Ritchie (1972) 2 stage model. Upper limit of stage 1 soil evaporation is calculated from soil texture as is the rate of stage 2 evaporation. Soil evaporation is limited by available water.	Storage routing through soil layers. WEPP can also simulate subsurface lateral flow and flow to drainage tiles and ditches. Water content exceeding field capacity drains to the next layer. Saturated hydraulic conductivity is calculated from soil texture, organic matter and porosity. It seems that unsaturated soil water movement is not considered.	Potential transpiration is the difference between PET and Soil Evap. Potential transpiration is distributed between layers based on root zone depth. Actual transpiration is limited by plant water stress which depends on soil water content	In soil where moisture is less than critical (the moisture content where plants become stressed) actual transpiration is based on the ratio of available moisture content to critical water content, otherwise, transpiration is at the potential rate	Hydrology component of WEPP calculates peak runoff rate, runoff duration, effective rainfall intensity, and effective rainfall duration. Soil detachment by rainfall is calculated. Hydrologic variables are input to a hydraulic model to calculate flow shear stress and sediment transport capacity. Transport is calculated on hillslopes, rills and channels.	Not used

Table A1 Summary of modelling approaches (continued)

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
1	AGNPS	P export is modelled from surface runoff. Approach adapted from CREAMS	N export is modelled from surface runoff. Approach adapted from CREAMS	SCS curve number Average land slope (%) Soil erodibility factor Soil texture	Not modelled	Chemical transport includes soluble and sediment adsorbed phases	Not modelled
2	ANSWERS	Not modelled	Not modelled	Surface storage coefficient Steady state infiltration rate Total porosity Field capacity Antecedent soil moisture USLE "K" Infiltration rate descriptors:(Infiltration control zone depth, Coefficient describing how the infiltration rate decreases as soil moisture content increases)	Not modelled	Not modelled	Not modelled
3	APSIM	includes the modules MANURE that models the release of P and SOILP that models transformation of P	Comprehensive processes for modelling N that in mineralisation of crop residues in the soil by the SOILN module, decomposition of crop residues at the soil surface by the RESIDUE module. Tracking of three pools of organic matter. This was in response to weakness in the CERES model and to improve modelling of N input from legumes and the changing rate of organic matter decomposition with soil depth. SOILN also models urea hydrolysis, nitrification and denitrification.	For SOILWAT: lower limit, drained upper limit, air-dry water content and saturated water contents and thickness of each soil layer. For APSIM-SWIM: moisture characteristic and hydraulic conductivity relationship for each layer	For SOILWAT deep drainage is based on water moving below the lowest soil layer. Unsaturated flow cannot lead to deep drainage. For APSIM-SWIM a range of boundary conditions can be specified at the base of the soil profile	1. Solutes move with saturated and unsaturated flow. Incoming and existing solutes are fully mixed to determine the concentration of water leaving a soil layer 2. Combination of Richard's equation and advection dispersion equation	Estimates of N leaching are based on concentration of N in water moving beyond the soil profile. APSIM has been used to estimate N leaching from cropping systems including wheat and sugarcane (Asseng et al., 1997; Verburg et al., 1996)
4	CERES	Not modelled	N is modelled as a limiting plant nutrient (via an N balance) rather than modelling N export as a pollutant. CERES models include a submodel, CERES-N.	Soil properties - Curve number - Drainage coefficient - Runoff coefficient - Evaporation coefficient - Soil surface albedo - Lower limit of plant available water - Field drainage upper limit - Rooting preference coefficients	Drainage from the entire soil profile the drainage from the lowest layer	Not usually modelled, but CERES was modified to predict pesticide leaching for a particular application (Gerakis and Ritchie, 1998)	Not modelled

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
				(weighting factors) for each layer (0-1) (depend on Soil type but generally decrease with depth). A value of 1 indicates soil hospitable to root growth - Field saturated Soil water content - Limit of first stage soil evaporation See Ritchie, 1998			
5	CREAMS	Models adsorbed phosphorus, solute phosphorus. Soluble P are leached from crop residue but does not more through the soil.	Models mineralisation, nitrification and denitrification, plant uptake and leaching by soil water movement out of the root zone. Enrichment ratios are used to estimate the portion of N transported with sediment	Soil profile is assumed to have constant hydraulic properties. Required parameters are: Saturated hydraulic conductivity Portion of plant-available storage filled at field capacity Soil porosity Immobile soil water content. Stage 1 soil evap parameter Soil density Depth of root zone Effective capillary tension Sand, silt and clay components	Water moving below the root zone. Estimated from averages and cumulative data rather than providing daily values	Pesticide component simulates foliar interception, degradation, wash-off, as well as soil processes of adsorption, desorption and degradation in soil. Soluble and sediment attached components are modelled. Sediment enrichment ratios are used	N is leached from crop residues into soil by the fraction of rainfall that does not runoff. N leached from soil is based on an N balance that takes account of N inputs, N uptake by plants, denitrification, mineralisation (organic N to nitrate). Leached N is deep drainage x concentration in root zone.
6	EPIC	Models soluble P loss in surface runoff. Assumes P conc in sediment is 175 times that in water. Attached P = sediment yield x concentration of P in soil x enrichment ratio.	For the top layer (10 mm of soil). Loss is a function of concentration x sum of (runoff, percolation and lateral subsurface flow). N can move upwards in water movement in response to evaporation and is supplied by rain. Similar approach in lower layers except there is no runoff. Uses a mass balance to track N. Particulate N based on sediment yield, N concentration in sediment and an enrichment ratio. Models denitrification as a function of temperature and water content. Models N mineralisation and immobilization	Soil albedo Number of soil layers Initial soil water content-fraction of field capacity Min depth to water table Max depth to water table Initial depth to water table Bulk density of each soil layer Oven dry bulk density of each layer Wilting point of each layer Field capacity of each layer Sand content of each layer Silt content of each layer Organic N concentration of each layer	Uses a water balance model to movement of the water table. Based on 30 day running sums of rainfall, runoff and potential evap. (The documentation says potential, but it seems it should be actual)	No modelling of solutes separately from N and P	N leaching is calculated from water leaving the lowest soil profile x N concentration
7	GLEAMS	Same as CREAMS	Same as CREAMS	Porosity Water retention characteristics Organic matter content	Daily values from water balance. An improvement from CREAMS was	Focus on pesticides. Similar modelling approach to CREAMS. Expanded the available	Same as CREAMS

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
					calculation of daily drainage values.	modelled pesticide application approaches. Improved pesticide degradation modelling. GLEAMS was tested using Bromide as a surrogate for a very mobile pesticide.	
8	GRASP	Not modelled	N is modelled as a plant nutrient, but the focus is not on N export. GRASP does not model the complete N cycle or transformations	Soil depth Moisture holding characteristics at air-dry, wilting point and field capacity throughout the soil profile	Based on drainage below the bottom of the lowest soil layer	Not a focus of the GRASP model	Not a focus of the GRASP model
9	HowLeaky	Calculates dissolved, particulate, total P and bioavailable P. P enrichment ratio accounts for P-rich fine material from hillslopes	Separate models for: 1. Dissolved N in runoff 2. Dissolved N in leaching 3. Particulate N in runoff Simple approach Does not use a nitrate volume balance or routing. Uses the method of Rattray or Fraser to calculate dissolved N in runoff after fertilizer application.	1. Number of horizons 2. Layer depth (mm) 3. Air dry moisture (% vol) 4. Wilting point (% vol) 5. Field capacity (% vol) 6. Sat. water content (% vol) 7. Max drainage from layer (mm/day) 8. Bulk density (g/cm^3) 9. Stage 2 evap CONA (mm day$^{-0.5}$) 10. Stage 1 evap limit U (mm) 11. Runoff curve num (CN) (bare soil) 12. CN reduction 100% cover CN reduction - tillage 13. Rainfall to 0 roughness (mm) (cumulative rainfall required to remove surface roughness) 14. USLE K factor 15. USLE P factor 16 Field slope (%) 17. Slope length (m) 18. Rill/interrill ratio (0-1) 19. Soil cracking 20. Max crack infiltration (mm) 21. Sediment delivery ratio	Cascading bucket. Loss from lowest profile layer is deep drainage. Rate is capped to a maximum (mm/day)	Routing approach: Initial solute concentration across soils layer and in rainfall and irrigation water. Mixing coefficient used to route solute through soil when rainfall or irrigation leads to drainage. (This approach is not used for N)	Simple approach to calculating dissolved N leaching load. Requires information on N concentration in soil profile to be input possibly from other biophysical models. Does not use volume balance or routing. Load is concentration in deepest soil layer x drainage x efficiency.
10	HSPF	The PHOS module models transport, plant uptake, adsorption/desorption, immobilisation and mineralisation of P.	Modules NITR and NITRX simulates N transport and soil reactions and tracks nitrate, ammonia and organic N, denitrification mineralisation, immobilization, fixation,	1. Coefficient and exponent in the soil detachment equation 2. Coefficient and exponent in the sediment wash-off equation 3. Potency factors (enrichment ratios) for scour and wash-off	Models transfer of water to groundwater (which reappears as baseflow), or lost to deep percolation. Can include lateral inflow to	Includes modules to simulate nonreactive tracers.	Can model N leaving as deep drainage. Also allows adjustment factors if leaching estimates are too large.

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
		Export includes P attached to sediment. P leaching is modelled.	volatilization of Ammonia and partitioning between particulate and soluble. N reactions are modelled separately for each soil layer. Export Includes N attached to sediment and leached N.	4. Soil layer storage capacities (field capacities and lower limits) 5. Parameters for infiltration equation 6. Fraction of groundwater inflow that is lost 7. Density of deep-rooted vegetation	groundwater storage or interflow.		
11	HYDRUS-1D	Not modelled	N is treated as a solute. Capable of simulating transformation of N through urea, ammonium, nitrite, nitrate, nitrogen gas and nitrous oxide. Export is calculated from advection, diffusion and gaseous transport	Horizontal and vertical saturated hydraulic conductivity Location of any impervious layers Locations of transitions between soil layers Soil characteristic curve Soils can be non-uniform	Lower boundary condition can be specified.	Solute transport equations model advection-dispersion in liquid phase and diffusion in gaseous phase. Includes modelling of solute reaction and degradation and transfer between liquid and gaseous phases. Multiple solutes can be modelled and can react and interact	Leaching is handled through the advection diffusion equation responding to specified boundary conditions for the bottom of the soil layer
12	LEACHM	Not mentioned in documentation	Simulates the transformation and flux of N between three N pools including mineral, NH-4 and NO-3. Mineralisation, nitrification, denitrification and volatilisation are modelled.	Profile depth Lower boundary condition Soil bulk density Saturated hydraulic conductivity Root flow resistance Upper boundary condition Molecular diffusion coefficient Dispersivity Segment thickness	A boundary condition can be specified for the bottom of the soil layer which will allow calculation of deep drainage	Advection-dispersion equation. Volatilisation and transformations can be modelled	Comprehensive modelling of N sources, sinks and transformations. Leaching calculated as N concentration of drainage below the soil profile
13	OVERSEER	Not modelled	N balance for the soil profile including inputs from rain, irrigation and fertilizer, mineralised soil organic matter and crop residue, outputs via volatilization and denitrification, plant update and leaching. Considers N export via leaching. Long term average annual values are produced by the model.	Soil water content at: - wilting point - field capacity - saturation - bulk density - saturated conductivity - profile drainage class (Good - Very Poor) - soil texture group (Light, medium, heavy) maximum root depth Wheeler, 2018b	Drainage occurs when soil water exceeds field capacity. Maximum drainage rate is limited by saturated hydraulic conductivity	Not modelled (other than N)	Nitrate leading is defined as N percolating below 1.5 m depth (Cichota et al., 2010)
14	PERFECT	Not modelled	Not modelled	Information for up to 10 soil layers Lower soil water limit (-15 bar)	Uses an algorithm from	Not modelled	Not modelled

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
				Upper soil water limit (field capacity) Saturated water content Bulk density Curve number Soil erodibility (K factor) Soil evaporation factors CONA and U	CREAMS/GLEAMS (Leonard et al., 1987) Cascading bucket. Loss from lowest profile layer is deep drainage. No restriction on water movement below the modelled soil layers.		
15	RUSLE	Not modelled	Not modelled	Surface roughness Soil moisture Root mass in the upper 100 mm of the soil profile	Not modelled	Not modelled	Not modelled
16	SWAT	P is partitioned into sediment bound and soluble fractions. Export includes application of enrichment ratio	Simulates N forms and transformations including nitrification, volatilisation, denitrification, plant uptake, N in residue. Calculates the amount of Nitrate in runoff, lateral flow, and leaching (blow the lowest layer). N in runoff includes sediment attached N and application of enrichment ratio	Information for soil layers Lower soil water limit (-15 bar) Upper soil water limit (field capacity) Saturated water content Bulk density Curve number	Drainage below the lowest soil layer can be partitioned to groundwater recharge and deep drainage	Pesticides are modelled in a similar way to GLEAMS and includes application efficiency, volatilisation, half-life in soil, wash off fraction. Leaching estimates based on percolation from soil layers	Leaching is based on loss of N from lower soil layers in deep drainage
17	SWIM	P export attached to particles is not modelled. Could model P as a solute	N can be modelled as a solute. N modelling has been undertaken at management scales using APSIM-SWIM e.g., Verberg et al. (1996).	Soil water retention curve for soil layers Boundary conditions at soil surface Boundary conditions at bottom of soil Initial conditions in terms of water content or matric potentials Root radius Root conductance	A time dependent boundary condition needs to be supplied by the user for the bottom boundary condition as one of four options: 1. variable matric potential gradient 2. Variable potential 3. Zero flux 4. Seepage with variable threshold suction. Option 2 can be used to specify a fluctuating water table	Uses the advection-dispersion differential equation. Solute initial and boundary conditions are specified along with source/sink terms	Can model N as a solute. Has been used to model nitrogen export and leaching under effluent irrigation (Snow, 1995; Snow, 1996; Snow and Bond, 1996)

No	Model	P export	N export	Required soil hydraulic properties	Deep drainage	Solute leaching	Nitrate leaching
18	WEPP	Not modelled	Not modelled	Random roughness Orientated roughness Bulk density Hydraulic conductivity Interrill erodibility Rill erodibility Critical shear stress	Water moving below the root zone is lost and is not tracked	Not modelled	Not modelled

Table A1 Summary of modelling approaches (continued)

No	Model	Limitations	Comments	References
1	AGNPS	AGNPS is an event based. This limitation was overcome with the release of AnnAGNPS	AGNPS v5 was released in 2018	Young et al. (1989) https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/?ss=16&navtype=BROWSEBYSUBJECT&cid=stelprdb1042468&navid=140100000000000&pnavid=140000000000000&position=Not%20Yet%20Determined.Html&ttype=detailfull&pname=AGNPS%20Home%20Page%20|%20NRCS
2	ANSWERS	Event based so water movement that is important at larger temporal scales is not modelled e.g., soil evaporation and transpiration	It appears that ANSWERS (the event-based model) is no longer being updated. ANSWERS-Continuous has been developed and incorporates elements of GLEAMS and EPIC.	Beasley et al., 1987; 1988
3	APSIM	Seems a comprehensive and flexible model that has been thoroughly test. The ability to include plug in modules makes the model highly adaptable	"Plug ins" can be developed to model components of farming systems as required	Keating et al., 2003 Documentation at https://www.apsim.info/ SOILWAT module https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/soilwat/
4	CERES	The focus of CERES is on crop yield rather than erosion, deep drainage, or export of N, P and solutes. APSIM builds on and improves many of the CERES algorithms	There are a variety of CERES model that apply to different crops e.g., wheat, rice, maize, barley, grain sorghum, pearl millet. Basso et al. (2016) provides a review of CERES model performance against measured values, including assessment of the simulation of soil water and ET. Contributors to CERES included Henry Nix (ANU)	Ritchie and Otter, 1985; Ritchie and Godwin, D. (n.d.) CERES Wheat 2.0 https://nowlin.css.msu.edu/wheat_book/ (accessed 19 Jan 2020)
5	CREAMS	Deep drainage is modelled by difference rather than explicitly. However, there are some validation data that show results are reasonable at annual time scales. Field scale model rather than watershed scale. Does not include N fixation by legumes.	CREAMS was built quickly which required adoption of existing models. The approach used in CREAMS has been highly influential with components widely adopted in other models.	Knisel, 1980
6	EPIC	1D model. Applicable to a small area.	Enrichment ratio function seem very approximate but in important for correct estimation of N and P loads. As well as the Erosion Productivity Impact Calculator, there is an Environmental Policy Integrated Climate Model which is called EPIC	Sharpley and Williams (1990); Williams et al., 1984
7	GLEAMS	Does not consider the recycling of solute (bromide, pesticides) back into the soil from plant residues. Not intended to accurately predict absolute quantities but	Modification of CREAMS to better represent movement of water within and through the root zone and improve long-term simulation. Computational structure altered to output daily values. In contrast	Leonard et al., 1987

No	Model	Limitations	Comments	References
		intended to show relative differences as responses to management actions	to CREAMS, GLEAMS allows for non-uniform soil characteristics. Future versions will model crop residue and its effect on erosion	
8	GRASP	Does not model the complete N cycle. Does not model run-on or lateral drainage The focus of the model is not on N or P export, N leaching or deep drainage.	CEDAR is a clean recoding of the GRASP	CEDAR GRASP manual 2019
9	HowLeaky	1. Event processes, which occur over < 1 day may be poorly represented. For example, erosion caused by a short duration intense storm. 2. One dimensional. Only applicable for field-sized areas with gentle slopes and with homogeneous soils, vegetation, topography and climate. Does have an option to calculate lateral flow on steep slopes.	PERFECT algorithms are available in HowLeaky by setting model options. An option to model infiltration in cracking soils is available. Doesn't have a sophisticated approach to modelling N so N export and leakage may not be as accurate of other models e.g., APSIM	HowLeaky Model V5 Technical documentation Version 1.06
10	HSPF	Calibration is challenging requiring experience and expertise. There is a lack of documentation on parameter estimation. Data requirements are extensive (Yuan et al., 2020).	The modular nature of HSPF means it should be straightforward to modify for specific applications. Focus on watersheds rather than hillslopes or fields.	EPA, USGS; WinHSPF 3.0; Public; https://www.epa.gov/ceam/basinsdownload-andinstallation Donigian et al. (1995)
11	HYDRUS-1D	Complicated, likely to have lengthy run times (but computers are getting faster all the time). Would need to have experienced users to set up and operate the model	Hydrus 1D is available for free. Hydrus 2D/3D are available commercially. The ability to model multiple solutes and their interactions could be important for some problems	Simunek et al. (2009)
12	LEACHM	Not effective in evaluating impacts of management practices on ground water loadings	If the complexity of using Richards equation is warranted, it may be better to use a model such as SWIM, APSIM-SWIM or HYDRUS which seem to be more flexible	Hutson and Wagenet (1995)
13	OVERSEER	1. Doesn't consider N in surface runoff or bound to particles.	The monthly time step for some results may be an issue in some cases	OVERSEER Nutrient budgets technical manual for the Engine (Version 6.3.0) www.overseer.org.nz
14	PERFECT	1. Processes which occur over < 1 day may be poorly represented. For example, erosion caused by a short duration intense storm. 2. One dimensional. Only applicable for field-sized areas with gentle slopes and with homogeneous soils, topography and climate. 3. Deep drainage is lost instantaneously. PERFECT does not consider any restrictions to water movement below the soil.	Many of the algorithms in PERFECT were adopted in later models e.g., HOW LEAKY?	Littleboy et al., (1999)
15	RUSLE	The RUSLE is restricted to estimating average soil loss	Prediction relationships developed from US data.	Renard et al. (1997)

No	Model	Limitations	Comments	References
16	SWAT	1. Not appropriate to model events (Yuan et al. 2020) 2. Does not consider the effect of season on vegetation growth (Qi et al. 2017)	SWAT is regularly updated, has an active user community and over 1300 relevant articles have been published	USDA-ARS; SWAT2012; Public; https://swat.tamu.edu/ Yuan et al. 2020
17	SWIM	1. Complex model with extensive data requirements 2. Does not model soil movement	SWIM was developed as a research tool but has recently been incorporated into APSIM (APSIM-SWIM) so can be used to address management problems. The link with APSIM also allows improved modelling of plant growth and transpiration	Verberg et al., (1996)
18	WEPP	Does not model N or solutes	Uses weather generation rather than requiring input of climate data. Can model irrigation	Flanagan and Nearing (1995)

Appendix B: Further research

The following topics are suggested as priorities for further research.

1. Deep drainage

In most water balance research, deep drainage is usually calculated as the closure term rather than being directly measured. That means that most of the error in water balance calculations will be lumped into deep drainage. A key question is how important is deep drainage really to the overall water balance? For those soil × climate × cropping situations where it is important, then more work should be undertaken to measure deep drainage and its consequences to the leaching of solutes. The paper by Steward et al. (2006) on deep drainage in irrigated sugar cane showed that actual behaviour of flow to/from groundwater can be complex.

2. Erosion

Sediment could be a significant pathway for pollutants and is currently not addressed by MEDLI. Therefore, it is important that the actual occurrence of erosion is minimised. This is a design issue rather than a modelling issue.

3. Runoff from irrigated paddock

Runoff from the irrigated paddock can be an important pathway for nutrients and pollutants to get into receiving waters (Mallin, 2000). Key processes need to be included in the MEDLI model.

4. Modelling of nitrogen

The stocks, flows and transformation of nitrogen are complex. It is important to seek expert advice on the best way of modelling nitrogen in MEDLI so that results are fit for purpose without excess complexity.

5. Comparison of actual and modelled performance

MEDLI has been around for several decades and has been used to design many systems. It would be appropriate to review how systems, designed with MEDLI, have actually worked, compared with how they were modelled. Findings could be used to set priorities for further research and improve the model.