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SALT LEACHING REQUIREMENTS FOR SOILS IN THE LOWER MURRAY RECLAIMED IRRIGATION AREA

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EXECUTIVE SUMMARY

Background

The Lower Murray Reclaimed Irrigation Area (LMRIA) is situated on the historical floodplain of the River Murray between Mannum and Wellington in South Australia and comprises various individual irrigation areas. In order to manage the effects of rising saline groundwater in the LMRIA, an Environmental Land Management Allocation (ELMA), is allocated on an annual volume per land area (ML ha^{-1} $year^{-1}$) basis. The amount allocated varies by irrigation area with the northern LMRIA region receiving a larger allocation than areas in the south.

Aims and methods

The aim of this report is to calculate the leaching requirement for soils in the LMRIA, including consideration of saline groundwater inputs. This was done for three locations - one location (Baseby irrigation area) representing the northern region, one (Long Flat irrigation area) representing the central region, and one (Jervois irrigation area) representing the southern region. Three different assessment methods were used, (1) estimated the volume of irrigation water required for maximum crop growth through a calculation of the potential water deficit from climate data, (2) calculated the volume of irrigation water that would be required to leach salt added from River Murray irrigation water and rainfall through use of a leaching fraction, and (3) calculated the volume of irrigation water required to manage the effects of rising saline groundwater through complex computer simulations of water and salt movement.

Key findings

1. The climate deficit calculations suggested 12–13 ML ha^{-1} $year^{-1}$ of irrigation water was required for maximum crop growth. These volumes are consistent with the irrigation allocations that were provided to LMRIA licensees when water entitlements were converted from an area based to volumetric allocation (13.92 ML ha^{-1} $year^{-1}$) and the current maximum irrigation water application rate allowable under the River Murray Water Allocation Plan. While drainage and leaching of salt would occur under these irrigation volumes, the amount is more than is required to just leach salt from the soil.

2. Simple leaching fraction calculations suggested the volume of water required to leach salt added from River Murray irrigation and rain water is very low (less than 2%) due to the low salinity of the river water. The leaching fraction increased marginally from the Jervois to the Baseby irrigation areas. However these calculations assume only downward movement of salt and, due to the presence of rising saline water tables, are not considered reliable to determine salt leaching requirements in the LMRIA.

3. Complex modelling with water and solute software (HYDRUS 1D) that accounts for saline water table rise was undertaken to better assess the LMRIA salt leaching requirements. A range of simulations were conducted for a number of different scenarios ranging from bare soil and no irrigation (Scenario 1), pasture with no irrigation (Scenario 2), irrigation of pasture on a 100 mm potential water deficit (Scenario 3), application of volumes of water equivalent to current ELMA allocations with different timings (Scenarios 4 and 5), and application of sufficient water (up to 200 mm in an irrigation) to prevent a critical concentration of salt at 0.5 m depth being reached (Scenario 7). Key results were as follows:

- Scenario 2 showed salt building up in the profile over time due to the lack of irrigation in this scenario. The results of this simulation would likely represent the situation if no ELMA or other irrigation water was available, as salt tolerant vegetation establishes in the absence of pasture and there tends to be little bare soil present in the LMRIA (as assumed in Scenario 1) unless there is waterlogging due to poor drainage.
- The Scenario 3 simulations showed salt successfully being leached from the soil profile. However, this was reliant on very large irrigation volumes being applied, similar to current commercial allocations (approx. 12−13 ML ha^{-1} $year^{-1}$) and providing sufficient water to meet crop demands for full production.
- Scenarios 4 and 5 applied irrigation volumes equivalent to the current ELMA allocations showed salt building up to higher levels at the Long Flat and Jervois sites, relative to the Baseby site. This is driven primarily by the current ELMA distribution with substantially higher (over double) allocations available and applied in the model at Baseby compared to Jervois.
- The Scenario 7 simulation attempts to maintain, via irrigation, the salt concentration at the bottom of the root zone at a set salt concentration of 13.9 kg m^{-3} which is equivalent to an EC_{se} of 8.96 dS m^{-1}. This is considered to be the most refined scenario for the purpose of calculating the salt leaching requirement while considering the effects of rising saline groundwater pressures in the LMRIA. The modelling results suggest that volumes of 5.71 (Baseby), 5.21 (long Flat) and 5.21 (Jervois) ML ha^{-1} $year^{-1}$ are required to keep the salt concentration at 0.5 m below critical values. The modelling suggested rye grass transpiration and productivity will be reduced about 50% with the average salinities (approx. 13 dS m^{-1} in a saturated paste extract) achieved in this Scenario at all sites.

Recommendations

The analysis here was fit for purpose for the request made, however there are limitations to these studies as indicated in this report. As a result, the following recommendations for further work are made:

1. Measurement of soil physical properties and soil salinities in different regions would be beneficial to better parameterise the model in different regions of the LMRIA.
2. The modelling results here are based on one soil, the water demands and salinity tolerance of one plant species (ryegrass), and a single water table salt concentration and water table height. While these were chosen to represent typical values in the LMRIA, pending the variability in the results from Recommendation (1) it would be prudent to do further simulations with varying of these conditions.
3. Controlled ELMA irrigation trials (at field scale or in mesocosms) and salinity measurements would useful to validate model results.
4. Given that the triggering of the irrigations in the HYDRUS simulations was based on salt concentration at 0.5 m depth, it may be useful to trial the measurement of soil salinity as a trigger for ELMA irrigation in the LMRIA. Currently irrigation in the LMRIA is typically triggered on observations of soil moisture conditions rather than salinity. Salinity may be a more appropriate indicator if salt leaching is the main outcome desired from the ELMA.

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1 INTRODUCTION

1.1 BACKGROUND

The Lower Murray Reclaimed Irrigation Area (LMRIA) is situated on the historical floodplain of the River Murray between Mannum and Wellington in South Australia and consists of various irrigation areas (Figure 1). This area has been farmed for over 100 years after drainage and reclamation. Following the "millennium drought", which resulted in cracking, formation of acid sulfate soils and salinization, various studies have been undertaken to assess the condition and remediation of soils (Mosley et al. 2014, 2016, 2017a,b; Fitzpatrick et al. 2017a,b). This has included detailed one and two dimensional modelling of irrigation requirements to prevent soil cracking and acidification at sites at Long Flat and Mobilong irrigation areas.

Land within the LMRIA is typically lower than the river level and highland groundwater level and as such is a natural discharge point for saline regional groundwater (Barnett et al. 2003). Soil salinisation can result if irrigation and drainage does not occur (Mosley et al. 2017a,b). Figure 2 shows a generalised conceptual model of the landscape and hydrology in the LMRIA. In order to manage the soil salinity in the LMRIA and prevent land degradation, an Environmental Land Management Allocation (ELMA), is allocated on an annual volume per land area (ML ha^{-1} $year^{-1}$) basis (SAMDB NRMB 2016). The amount allocated varies with irrigation area, with areas in the north getting a larger volume than areas in the south (Table 1). The climate varies from the north to the south with drier, hotter conditions in the north and wetter, cooler conditions in the south.

This report assesses the leaching requirement for saline groundwater inflows to prevent soil salinisation for three (northern, central, southern) regions within the LMRIA. Three different assessment methods were used; (1) estimated the volume of irrigation water required for maximum crop growth through a calculation of potential water deficit from climate data, (2) calculated the volume of water that would be required to leach salt added from River Murray irrigation water through use of a leaching fraction calculation, and (3) calculated the volume of water required to manage the effects of rising saline groundwater through complex computer simulations of water and salt movement (HYDRUS 1D).

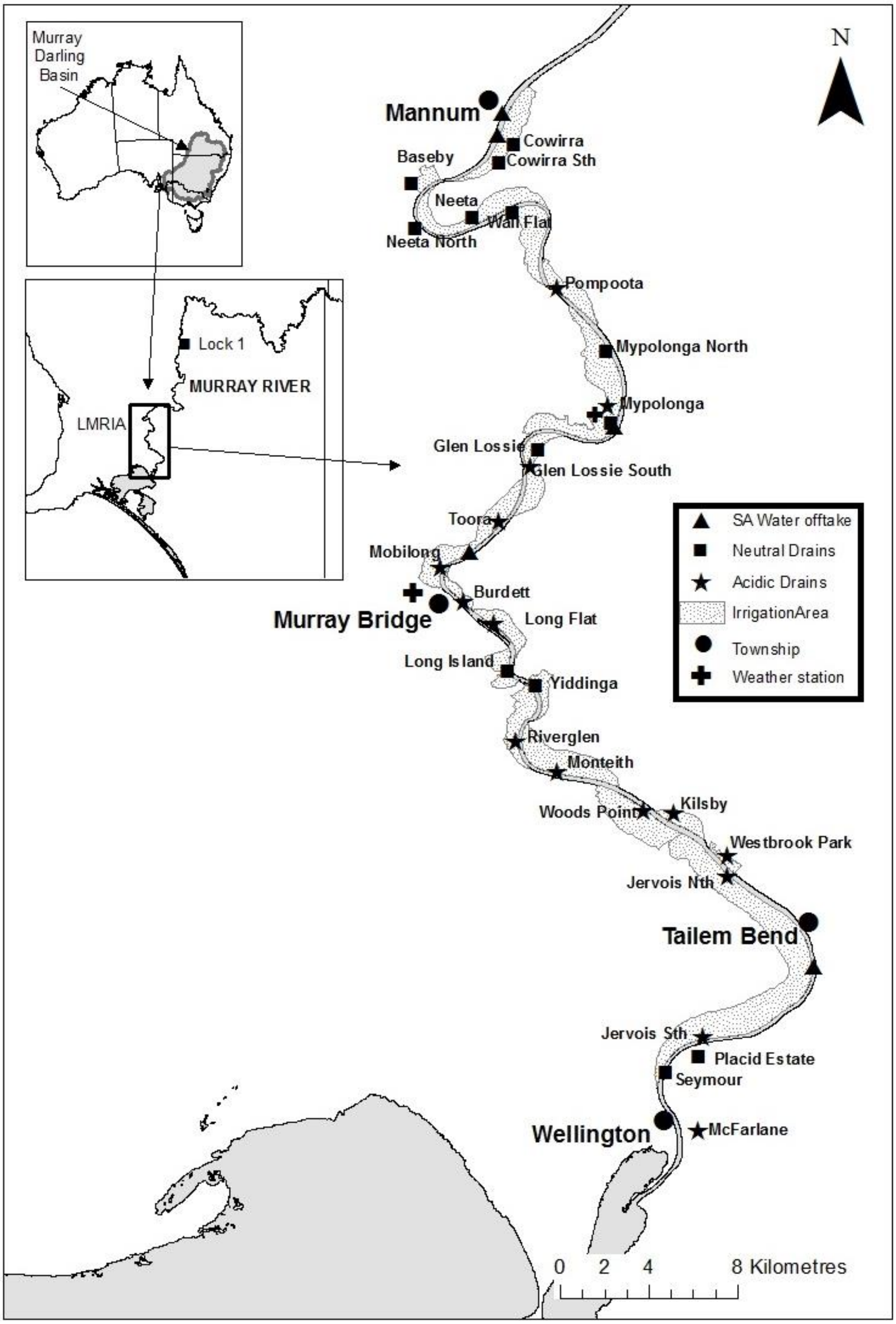

Figure 1.Lower Murray Reclaimed Irrigation Area region showing the location of individual irrigation areas (from Mosley et al. 2016a).

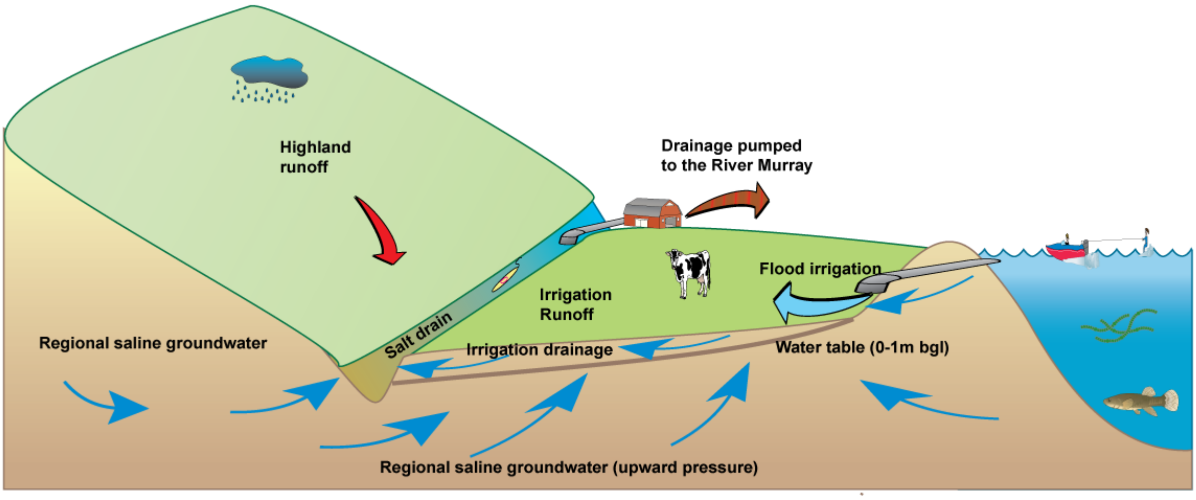

Figure 2 Conceptual model of the landscape and hydrology in the LMRIA.

1.2 WATER ALLOCATION AND CLIMATE DATA

Rates of application for ELMA are presented in Table 1 (SAMDB NRMB 2016). Three irrigation areas were chosen to represent the north (Baseby irrigation area), middle (Long Flat irrigation area) and south (Jervois irrigation area) of the LMRIA. The climate data (rainfall; potential evapotranspiration (PET) for these three sites was obtained from the Queensland Government Long Paddock website (https://www.longpaddock.qld.gov.au/climateprojections/access.html) for the locations identified in Table 2. PET from Long Paddock and used in the simulations was based on the FAO56 short crop estimation procedures (FAO, 1988).

Table 1. LMRIA – rates of application for ELMA (SAMDB NRMB 2016). The irrigation areas in bold are the ones assessed in this study.

Irrigation Area	ELMA Rate (ML ha^{-1})	Irrigation Area	ELMA Rate (ML ha^{-1})
Cowirra	6.49	Mobilong	4.68
Neeta North	6.14	Burdett	4.56
Baseby	**6.44**	**Long Flat**	**4.46**
Neeta	6.23	Long Island	4.22
Wall Flat	6.06	Swanport	4.15
Pompoota	5.86	Yiddinga	4.13
Mypolonga	5.50	River Glen	3.98
Burbridge	5.37	Monteith	3.87
Paiwalla	5.15	Kilsby	3.61
Glen Lossie	5.10	Woods Point	3.58
Toora	4.87	Westbrook	3.46
Jervois	**2.96**	Seymour	2.33
Finniss	1.38		

Table 2. Location of irrigation districts, total rainfall and PET for the 51 year period from 1960-2010. The mean annual potential water deficit (PWD) is calculated from the rainfall and PET. The irrigation areas in bold are the ones used in this study.

Irrigation Area	**Latitude**	**Longitude**	**Total Rainfall 1960–2010** (mm)	**Total PET 1960–2010** (mm)	**Mean annual PWD** (mm)
Baseby	**-34.947**	**139.269**	**14948.5**	**82055.0**	**1316**
Pompoota	-34.993	139.343	15346.9	82222.8	1311
Mobilong	-34.107	139.272	17103.3	80868.1	1250
Long Flat	**-35.129**	**139.307**	**18085.7**	**80073.9**	**1215**
Monteith	-35.186	139.336	18469.9	79720.5	1201
Woods Point	-35.206	139.370	18469.9	79720.5	1201
Jervois	**-35.252**	**139.437**	**18259.7**	**80663.8**	**1224**

2 Irrigation Requirements Based on Climate Deficit Calculations

A climate deficit calculated method was used to estimate the irrigation volumes required to meet evapotranspiration losses from the soil, once rainfall is taken into account. This method does not consider the volume of water required to manage salinity. These calculations approximate the volume of water required to produce maximum crop growth.

The number of “climate deficit” irrigations and total irrigation volume were calculated from the climate data by calculating the cumulative potential daily water deficit (*WD*, mm) by:

$$WD_i = \sum_{i=1}^{n} P_i - PET_i \qquad (1)$$

where:

P_i = rainfall on day i (mm)

PET_i = potential evapotranspiration on day i (mm)

i = the day counter

When *WD* is less than -100 mm then WD_i is set to WD_i + 100. When irrigation is recorded, value of i increases by 1. The final value of i is then the number of 100 mm irrigations that would be required to meet the atmospheric water demand.

The estimated total number of irrigations over the 51 year period to meet the 100 mm climate deficit varied from 671 at Baseby to 612 at Woods Point (Table 3). The average amount of irrigation required under this climate deficit method was between 12−13 ML ha^{-1} yr^{-1}.

Table 3. Estimated number of irrigations (over 51 year period) and irrigation water required. The irrigation areas in bold were the sites modelled in this study.

Irrigation Area	**Number of Irrigations estimated using *WD***	**Irrigation water required annually** ML ha^{-1} yr^{-1}
Baseby	671	13.42
Pompoota	668	13.36
Mobilong	637	12.74
Long Flat	619	12.38
Monteith	612	12.24
Woods Point	612	12.24
Jervois	624	12.48

The climate deficit method assumes that all of the water applied is used for evapotranspiration and no water table or drainage impediment exists in the soil. The assumption that the actual evapotranspiration is equivalent to the potential evapotranspiration means that this scenario applies more water than the crop will require and results in further drainage of water from the soil profile. If rainfall occurred following an irrigation it would also contribute to drainage from the soil and leaching of salt. The high drainage using a climate deficit compared to other irrigation scenarios can be observed in the HYDRUS model results presented for "Scenario 3" below. In essence, the climate deficit method over-estimates the irrigation required solely for leaching salt.

The assumption in the climate deficit method that no drainage impediment exists is also not applicable to the situation in the LMRIA where shallow water tables are present (Figure 2, Mosley et al. 2016). The potential effects of a lack of drainage (due to shallow water table), and potential limitations on salt leaching, are not taken into account in the simple climate deficit method. If a lack of drainage results in limitations in salt leaching, crop growth limitations may occur. Nevertheless, it is noted that the volumes of irrigation required for maximum crop growth are similar to the volumes of irrigation allocations originally granted in the LMRIA and the maximum irrigation water application rate allowable under the River Murray Water Allocation Plan (WAP, SAMDB NRMB 2016) of 13.92 ML ha^{-1} $year^{-1}$. The average number of 100 mm irrigations predicted per year of 12ML/ha to 13 ML/ha (Table 2) is also quite consistent with findings of previous studies (Philcox and Douglas, 1990; Mosley and Fleming, 2009).

Key findings: the climate deficit in the LMRIA suggests application of 12−13 ML ha^{-1} yr^{-1} of irrigation water would be required to meet requirements for maximum crop growth. This is consistent with the volume of irrigation allocations that were provided to licensees when water entitlements were converted from an area based to volumetric allocation (13.92 ML/ha) and the maximum irrigation water application rate allowable in the LMRIA under the River Murray Water Allocation Plan.

3 Irrigation Requirements Based on Salt Leaching Fraction Calculations

Leaching of salts is required to prevent salinisation of the root zone of the crop. Calculation of the "leaching fraction" (LF) is a simple method to estimate the extra irrigation water that needs to be applied to the soil to ensure the amount of salt in irrigation and rain water is leached from the soil profile to prevent salinisation. The method does not calculate the additional irrigation volume required to leach salt which is derived from any saline groundwater discharge, and assumes a steady state salt balance.

Specifically, the leaching fraction is defined as the proportion of applied water (irrigation + rainfall) that drains below the root zone in the soil profile. On the assumption that the water draining at the bottom of the root zone is equivalent to the soil matrix salinity, the LF can be calculated using (ANZECC, 2000 eqn 9.2):

$$LF = \frac{EC_i}{EC_d} = \frac{D_d}{D_i} \tag{2}$$

where:

EC_i = electrical conductivity of water entering soil (rainfall + irrigation) (dS m^{-1})

$$EC_i = \frac{EC_r D_r + EC_{iw} D_{iw}}{D_r + D_{iw}} \tag{3}$$

EC_d = electrical conductivity of drainage water below the rootzone (dS m^{-1})

EC_r = electrical conductivity of rain taken as 0.10 dS m^{-1} (Crosbie et al., 2012)

EC_{iw} = electrical conductivity of irrigation water 0.252 (dS m^{-1}) (Mosley et al. 2017a)

D_r = rainfall depth (mm yr^{-1})

D_{iw} = depth of irrigation water (mm yr^{-1})

D_d = depth of water draining from the soil to maintain EC_d (mm yr^{-1})

D_i = depth of water applied to the soil (D_r + D_{iw}) (mm yr^{-1}).

The values for the above parameters used in calculating the leaching fraction are given in Table 4.

Table 4. Parameters used in calculating the leaching fraction and drainage depth. The rainfall depth values (D_r) for the three areas represent the driest, mean, and wettest years respectively in the 51 year climate record from 1960-2010.

Parameter	Value	Units
EC_d	11.2	dS m^{-1}
EC_r	0.10	dS m^{-1}
EC_{iw}	0.252	dS m^{-1}
D_r		
Baseby	97.5, 293.1, 565.3	
Long Flat	131, 354.6, 598.6	mm yr^{-1}
Jervois	146.8, 358, 568.2	

Salinity in the root zone decreases the osmotic potential in the soil solution. This causes plants to exert more energy to take up soil water to meet their evapotranspiration requirement. At certain soil-profile salt concentrations, plant roots will not be able to generate enough force to extract water from the soil profile. Water stress will then occur, resulting in reduction of crop growth and yield. The extent to which the plants are able to tolerate soil salinity differs among crop species and varieties, and is discussed in detail in Cook et al. (2006) and Tanji and Kielen (2002).

Rye grass is a salt tolerant pasture type common in the LMRIA but other less salt tolerant pastures (e.g. clover and improved pasture species) are also present, as is salt tolerant vegetation (e.g. samphire, saltbush) on areas receiving little irrigation. Philcox and Scown (2012) found that 81% of LMRIA properties surveyed post the 2007-2010 drought period had pasture present which included both improved ryegrass, clover and older paspalum/kikuyu pasture. Winter mix (annual ryegrass and ryecorn) and lucerne were also present at several properties.

A range of D_{iw} values from 100 to 1000 mm yr^{-1} were used to calculate the leaching fraction for all three values of D_r as well as the value for the volumes equivalent to ELMA. The results show that the leaching fraction for these sites is very low at less than 2% due to the low salinity of the Murray River water (Figure 3). The leaching fraction decreases marginally from the Jervois irrigation area to the Baseby irrigation area due to the rainfall depth increasing (Table 5).

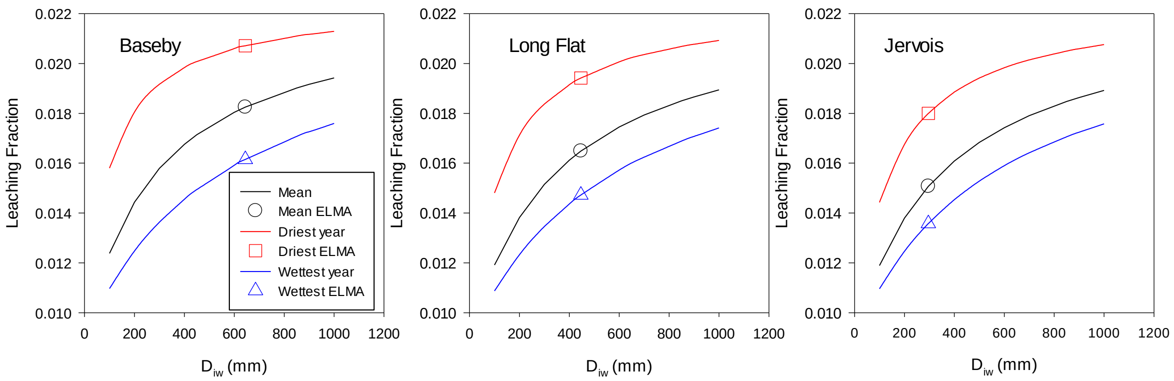

Figure 3. Leaching fractions calculated with equations (2) and (3) for the Baseby, Long Flat and Jervois sites for the mean annual rainfall, driest and wettest years in the 51-year period from 1960-2010. The symbols show volumes equivalent to the annual ELMA irrigation.

These simple calculations suggests that a minimal (1−2%) additional volume of irrigation water, to the volume required to keep salt at the bottom of the root zone at the threshold value (for 50% yield of rye grass), would be required to prevent soil salinisation.

Table 5. Leaching fractions for the Baseby, Long Flat and Jervois sites for volumes equivalent to the annual ELMA irrigation allocations for the mean annual rainfall, driest and wettest years in the 51-year period from 1960-2010.

Irrigation Area	**Leaching Fraction**		
	Mean	**Driest year**	**Wettest year**
Baseby	0.0183	0.0207	0.0181
Long Flat	0.0165	0.0194	0.0147
Jervois	0.0151	0.0180	0.0136

A major limitation of these simple leaching fraction calculations for use in the LMRIA, where a shallow rising saline water table exists (Figure 2), is that they do not allow for capillary rise of water and salt up the soil profile from the saline groundwater. This process is particularly effective in clay soils with small pore spaces The saline rising water tables can affect surface soil salinities (Mosley et al. 2017a), and pasture roots also extract water from the groundwater during dry periods (Philcox and Murray 1990) which draws up salt. This means that much higher salt leaching fractions than indicated in the simple calculations will be required and more sophisticated modelling techniques are needed to assess these as provided in the next section.

Key findings: simple salt leaching fraction calculations show that to remove the salt added to soil from application of the River Murray irrigation water and rainfall, only a small amount of extra water would be required. While the leaching fraction is applicable in the LMRIA to prevent the build-up of irrigation and rain water derived salt in the soil, it has to be in addition to any water that is applied to ameliorate the accumulation of salt in the soil due to shallow rising water tables. To assess the salt leaching requirements, measurements of the soil physical and hydraulic properties and modelling with water and solute software that allows for water table rise to occur is required.

4 COMPLEX WATER & SALT TRANSPORT SIMULATION MODELLING USING HYDRUS 1D

The HYDRUS 1D modelling software (Simunek et al. 2008) was used to represent the complex water and salt movement in the LMRIA soils in order to estimate the salt leaching requirements. Unlike the simple leaching fraction calculations (Section 3), this gave the capability to include the influence of rising saline groundwater discharges. HYDRUS 1D solves water and solute transport in variably saturated soils using the Richards and coupled convective dispersion equations (Simunek et al. 2012). These are solved using a finite element method. The model requires the material properties of the soil, initial and boundary conditions (rainfall, PET, irrigation, groundwater level and pressure head) and discretisation of both the spatial and temporal domains. HYDRUS models have been successfully developed and validated in the LMRIA over the last 5 years (Mosley, Cook et al. 2014, 2017a).

4.1 SOIL PROPERTIES

The soil properties used in the HYDRUS 1D model were based on those measured from three soil cores at Long Flat at three depths. For comparison purposes, and lack of suitable data in all locations, the same soil properties have been used for each of the different locations modelled. In general terms the soil properties are fairly uniform across the LMRIA (Taylor and Poole, 1931).

The moisture retention characteristics of these soils were measured on three samples taken from each depth giving a total of 9 measurements per depth (Figure 4).

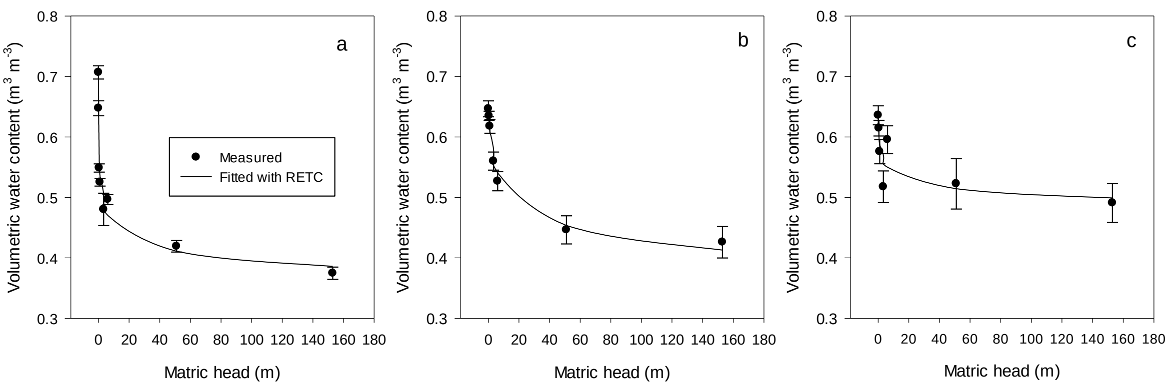

Figure 4. Moisture retention characteristics for the soil at Long Flat for depths of: a) 0-0.1 m, b) 0.1-1.0 m and c) > 1.0 m. The data points represent the mean value of the six measurements and the bars are the standard error. Of note is the reduction in the range of water content as the soil depth increases.

The van Genuchten equation (van Genuchten, 1980) was fitted to the average data using the RETC software (van genuchten et al., 2004). The parameters from the fit are shown in Table 6 and the fits to the data in Figure 4. The saturated hydraulic conductivity was taken from Mosley et al. (2016) based on earlier measurements at the Long Flat site. These values were used in modelling the water transport in HYDRUS 1D.

Table 6. Van Genuchten parameters for the soil at the Long Flat site for the three depths that were used in the LMRIA HYDRUS model. The parameters are: θ_s saturated water content, θ_r residual water content, α a parameter related to the air-entry value of the soil and n a shape parameter related to the slope of the curve.

Depth	**Van Genuchten parameters**				
(m)	θ_s	θ_r	α (m^{-1})	n	K_s (m day^{-1})
0-0.1	0.726	0.225	38.21	1.3081	1.3
0.1-1.0	0.652	0	1.60	1.0832	1.3
>1.0	0.651	0.384	10.32	1.1437	1.3

4.2 Water and Soil chemistry

The ground water salinity was calculated from measurements in a bore at Long Flat (Mosley et al. 2014), dissolved concentrations of anions and cations were used to calculate the total dissolved salts (TDS, kg m^{-3}) (Table 7). The irrigation/River Murray water TDS was calculated[1] from the electrical conductivity (EC, dS m^{-1}) by EC x 0.64 which gives the concentration in kg m^{-3} using measurements made of the river water EC in the experiments of Mosley et al. (2017a). The rainwater TDS was calculated from the mean EC for Adelaide (Crosbie et al. 2012). The TDS was used as the HYDRUS model calculates the EC from the concentration, and then compares the EC with the threshold value to decide if the solute stress will affect the transpiration.

Table 7. Estimation of ground water total dissolved salts (TDS) from bore LF1C at the Long Flat site, river water from Mosley et al. (2017a) and rain water from Crosbie et al. (2012).

Water source	**EC (dS m^{-1})**	**TDS (kg m^{-3})**
LF1C bore		6.18
River water	0.252	0.1613
Rainwater	0.12	0.0788

In HYDRUS, salinity in the soil is expressed in mass of solute per amount of liquid phase in the soil. This is equivalent to TDS in the soil solution and TDS in kg m^{-3} can be converted back to EC units (dS m^{-1}) by dividing by 0.64.

4.3 Spatial and Temporal domains of the Simulations

The spatial domain for the simulations consisted of three soil layers: 0−0.1 m, 0.1−1.0 m and 1.0−3.0m. The soil properties corresponding to each depth are given in Table 6. The model domain was split into 301 depth increments of 0.01 m each.

The temporal extent of the simulations was for 51 years. A time length of this magnitude cannot be directly handled by HYDRUS1D, so the time was split into two simulations 0−10,000 days and 10,000−18,628 days. The final conditions for the first simulation were copied into the second simulation as the initial conditions. After some initial experimentation an initial time step of 0.001

[1] See https://prod.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_067096.pdf

days, minimum time step of 0.00005 days and maximum time step of 5 days were chosen. Because daily meteorological data was used the actual maximum time step the model used was only 1 day.

4.4 Boundary and Initial Conditions

The boundary conditions for the simulations were atmospheric at the top boundary and a constant water pressure bottom boundary condition where a head of 2 m was maintained. The bottom boundary condition meant that a water table was maintained at 1 m depth in the soil as typically found in the LMRIA. The water tables in the LMRIA are controlled by the drain depth and pumping operations. Without sufficient drainage channels and pumping, water tables can rise to the surface and impact soil and vegetation quality. The results of the modelling are only relevant to this boundary condition which is considered most appropriate for the general situation in the LMRIA. The solute concentration on the bottom boundary was kept constant at 6.18 kg m^{-3} which was the measured value for the highland regional ground water at the Long Flat site (Table 7).

The potential evapotranspiration (PET) from the meteorological data set was split into potential evaporation (0.25 PET) and potential transpiration (0.75 PET) based on assuming a leaf area of index of greater than 3 (Sutano et al. 2012). The HYDRUS model then determines if this potential evaporation and/or the potential transpiration can be achieved depending on the soil conditions.

The rainfall was determined from the meteorological record and the salt concentration taken from Table 6. When irrigation occurred, this was inputted as rainfall by adding the required amount of irrigation to any rainfall in the input time series. The concentration of the surface water input when irrigation occurred was calculated as a volumetric mixture of rainfall and river water concentrations, so that the mass of solute inputted was correct.

The initial water pressure distribution was taken as a linear decrease from -1 m of matric head at the soil surface to 2 m at a depth of 3 m (the bottom boundary). This resulted in the soil water content being saturated from 1 to 3 m depth. The initial solute concentration in the soil water was taken as a linear increase from 6.18 kg m^{-3} at 3 m depth to zero at the surface. This gave a value of 1.03 kg m^{-3} (approx. 0.8 dS m^{-1}) at 0.5 m depth (the bottom of the root zone). Other initial values were experimented with but this appeared to be a reasonable value based on available data for the LMRIA surface soils on irrigated properties.

The crop was assumed to be pasture with a rooting depth of 0.5 m (where 90% of pasture roots occur, Philcox and Douglas 1990) and the appropriate values for the matric head transpiration reduction parameters were chosen as well as osmotic reduction in the transpiration using the threshold multiplicative model in HYDRUS 1D for rye grass (Table 8). As noted above other less tolerant pasture species may be present on some farms (Philcox and Scown 2012), these would require more irrigation water to achieve their salt leaching requirements. HYDRUS 1D will reduce the water uptake and hence transpiration by assessing the matric head and solute (osmotic) stress within the root zone. The ratio of the potential transpiration to the simulated transpiration was used to assess the likely reduction in grass growth. The direct relationship between transpiration and yield is a robust and well-known correlation (Hanks, 1983) and we use transpiration as a surrogate for yield in the results below. The method used to reduced transpiration in HYDRUS1D is also introduced below, to provide an understanding as to how this is done in the model. Water uptake by roots in the model is subject to a much more complicated process which also includes the root density and water potential. For a more complete understanding please refer to Simunek et al. (2012).

In HYDRUS1D a number of methods are available to include the effect of salinity on water uptake by plant roots. We have chosen the multiplicative model (Maas 1990). This uses a threshold value at which reduction in water uptake is triggered and a slope factor (S) for how fast the uptake is reduced as the salinity increases (Table 8) given by:

$$R = 1 - 0.01S\left(c - c_T\right) \tag{4}$$

where R is the reduction factor which varies linearly from 1 at c_T to zero at a maximum value of $c_m = c_T + 1/\left(0.01S\right)$, c_T is the TDS concentration associated with the threshold EC_{se} value (kg m^{-3}) and c is the TDS concentration of the soil solution (kg m^{-3}). The threshold concentration can be estimated from the threshold EC_{se} (dS m^{-1}) by[1]:

$$\begin{aligned} c &= 0.64EC, \quad 0.1 < EC \leq 5 \\ c &= 0.8EC, \quad EC > 5 \end{aligned} \tag{5}$$

For the threshold value for rye grass of EC_{se} = 11.2 dS m-1 this results in a c_T of 8.96 kg m^{-3} and with S = 3.8 (Table 8) a value of c_m for rye grass of 35.28 kg m^{-3}. The equivalent EC_{se} of c_m is not strictly able to be determined as the water content needs to be known, but if we assume the soil is at field capacity a good approximation is to divide the concentration by two and using eqn (5) this would give a maximum EC_{se} of 22 dS m^{-1}.

For rye grass the relative yield (Y_r, *%*) can be estimated with the following equation (FAO 2002):

$$Y_r = 100 - B(EC_{se} - A) \tag{6}$$

where A = the salinity threshold expressed in dS m; B = the percentage productivity decrease per dS/m increase above the threshold value; and EC_{se} = the mean electrical conductivity of a saturated paste taken from the root zone. To calculate the EC_{se} at 50% yield the equation can be re-arranged:

$$EC_{se\ 50\%} = A + (50/B) \tag{7}$$

To represent an approximately 50% yield of perennial rye grass, from equation 5 using values of A = 5.6 and B = 7.6 the $EC_{se\ 50\%}$ = 12.2 dS m^{-1} (FAO 2002) and zero yield at 18.8 dS m^{-1}. By comparison an R of 0.5 would occur at an estimated EC_{se} of 13.8 and R = 0 of 22 ds m^{-1} thus the HYDRUS1D model is expected to give estimates of transpiration reduction which are less that the yield reduction if estimated with the FAO (2002) method. This is because the two methods are different, one is a static measurement based on the EC of a saturated paste and the other is based on a dynamic model of solute concentration.

In scenarios with sufficient irrigation water application, salt can be leached from the soil profile (lost from model domain as drainage) but where insufficient water is applied the plants will take water up from the water table (via capillary rise) and salts will concentrate in the profile.

Table 8. Values used for reducing transpiration in the HYDRUS 1D model. The Feddes et al. (1974) model is used for the water stress due to matric head with the parameters for pasture from Wesseling (1991). The multiplicative model is used for solute stress and the values are from Maas (1990).

Water Stress (Feddes) Parameters	**Values**	**Comments**
PO (m)	-0.1	Value below which water uptake starts
POpt (m)	-0.25	Value at which optimum water uptake starts
P2H (m)	-2	Value at which optimum uptake reduction starts at high potential transpiration rates
P2L (m)	-8	Value at which optimum uptake reduction starts at low potential transpiration rates
P3 (m)	-80	Value of low limit for water uptake
r2H (m day^{-1})	0.005	Potential transpiration above which P2H is used
r2L (m day^{-1})	0.001	Potential transpiration at or below which P2L is used
Solute stress parameters		
Threshold (dS m^{-1})	11.2	Threshold at which osmotic stress reduces water uptake, with the salinity measured as a saturated paste (EC_{se})
Slope (S)	3.8	Slope of the curve determining the fractional root water uptake decline per unit increase in salinity above the threshold

4.5 Simulation Scenarios

Seven simulation scenarios were assessed for each of the three LMRIA locations/regions (Baseby, Long Flat, Jervois) as follows:

1. This simulation was run with no pasture and only evaporation from the soil surface and no irrigation. This simulation is of a bare soil situation if no irrigation was applied. This is hypothetical and is unlikely to be realistic under most circumstances as discussed for Scenario 2.
2. This simulation was run with pasture and no irrigation as an indication of what would happen if no irrigation was applied. This is likely the most realistic simulation if no water was available, as salt tolerant vegetation (i.e. samphire and saltbush) establishes in the absence of pasture and there tends to be little bare soil present in the LMRIA (even without irrigation) unless waterlogging occurs due to poor drainage.
3. This simulation was run based on irrigation on a climate deficit as explained in Section 2 above with no restrictions on irrigation allocation. From the meteorological data, the cumulative potential water deficit (PWD) was determined and for each -100 mm of PWD an irrigation of 100 mm was scheduled and resulted in N number of irrigations over the 51 year period. This scenario follows the suggestion by Philcox and Douglas (1990). This depth of irrigation is consistent with typical irrigation applications in the LMRIA that are on the order of 0.6 to 1.9 ML ha^{-1} per watering on average (60 to 190 mm depth) (Mosley and Fleming 2009).
4. In this simulations, ELMA allocations are used to scale the amount of water applied in Scenario 3. From the points in time where the irrigations in Scenario 3 were scheduled, volumes equivalent to ELMA was allocated in the model simulation by multiplying the annual ELMA allocation by 51 (to represent 51 years of simulation time) and the dividing by

N. This keeps the timing of irrigation as predicted by the PWD but applies volumes equivalent to the ELMA volume to the soil-pasture.

5. In this simulation, the irrigation volume equivalent to the total ELMA allocation for 51 years at a particular irrigation area was divided into a number (NE) of 100 mm irrigations. This is different from N above (number of 100 mm irrigations based on climate deficit, resulting in a much larger total irrigation amount). From the total PWD at the end of 51 years (PWD51) the triggering deficit (TD) was determined as TD = PWD51/NE. From the table of values of PWD (Table 2) the timing of irrigation could be determined when each additional TD amount of deficit had occurred.
6. In this simulation, the HYDRUS water content was used to trigger irrigation rather than PWD. The irrigation was triggered using the option in HYDRUS 1D when the matric head reached less than -2 m. Due to the constant pressure bottom boundary this did not work and has not been reported on in this report.
7. In this scenario, the salinity is used to trigger irrigation rather than PWD or HYDRUS water content. The Scenario 4 simulation for the Baseby site showed that at a depth of 0.5 m (bottom of root zone in model), after an additional accumulation of salt over the first 10 years of simulation a steady state was reached (Figure 5). Thus, in Scenario 7 irrigation was triggered when a critical concentration of 13.9 kg m^{-3} (equivalent to an EC_{se} of 8.96 dS m^{-1}) at 0.5 m depth (CC) was implemented. This value of the EC is less than the threshold value for rye grass (11.2 dS m^{-1}) used in HYDRUS, values greater than this reduce the transpiration and hence plant productivity. The reduction in yield calculated at this EC value is 89% (using equation 4), but overall the yield loss will be variable as the EC will reduce after irrigation and then over time build up to this threshold again before irrigation is again triggered. This scenario was time consuming to perform as it had to run until CC was reached and irrigation was added to the rainfall file at this time and the simulation rerun and the next CC time determined. This continued until 51 years of time were completed. In running this scenario, it was found that unless 50 mm of rainfall occurred at the irrigation time then the irrigation needed to be of 200 mm irrigation depth to achieve drainage of the salt beyond 0.5 m depth in the soil.

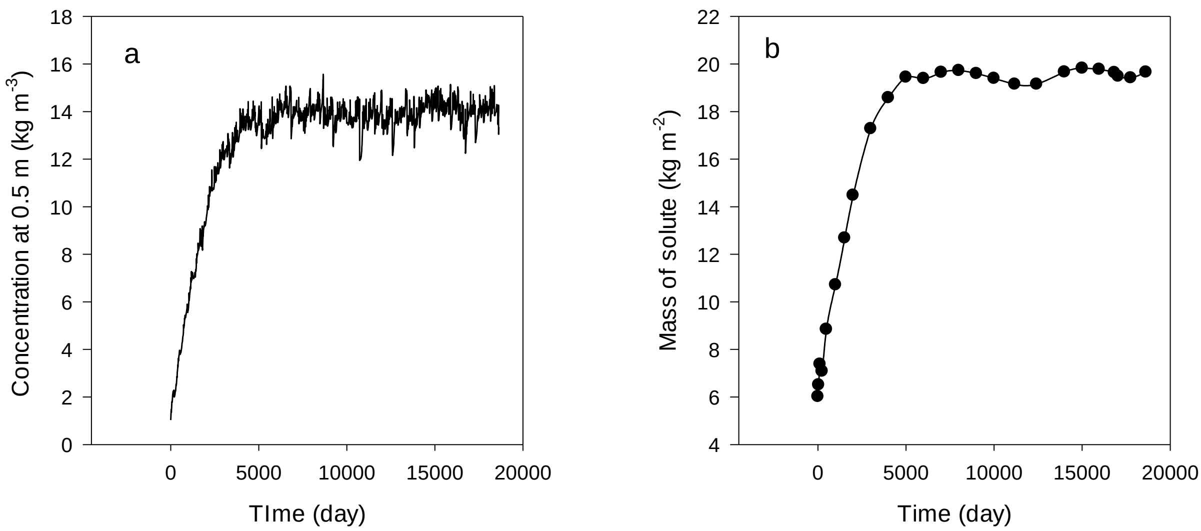

Figure 5 Irrigation of volumes equivalent to ELMA at the Baseby site a) the concentration of salt at a depth of 0.5 m with time and b) the mass of salt in the soil to a depth of 3 m with time.

A further set of simulations was carried out for scenarios 4, 5 and 7 with a free drainage bottom boundary condition and initial condition of matric head of -1m for all depths. These simulations were required for comparison with the leaching fraction estimations above.

4.6 SIMULATION RESULTS

The results will be presented firstly for each of the scenarios and each of the individual sites (Baseby, Long Flat, Jervois) and then the results compared between sites. The model was run for a period of 51 years (18250 days). Large changes in the model "warm up" period (first approximately 10 years) occur in many simulations that relate to both the initial conditions chosen and different irrigation scenarios being modelled.

4.6.1 Baseby

The Baseby site is the northern most site and was used to represent this region of the LMRIA. The results from the bare soil simulation (Scenario 1) suggested that the salt concentration at the base of the root zone (0.5 m depth) would decrease with time as would the total mass (Figure 6). This occurs because the soil surface dries and evaporation decreases below the PET, so that when rain occurs it results in drainage from the soil profile and hence salt loss to the ground water (Table 9). The ratio of ET/PET (in this case only E to PET as bare soil) is low at 0.152 (Table 9), which is why in this case the rainfall is able to flush the salt from the soil. However, this scenario is not likely to be realistic as salt tolerant vegetation is likely to establish in the absence of pasture and recent field trials with bare soil showed severe salinisation occurred quickly (few months) without irrigation (Mosley et al. 2017a).

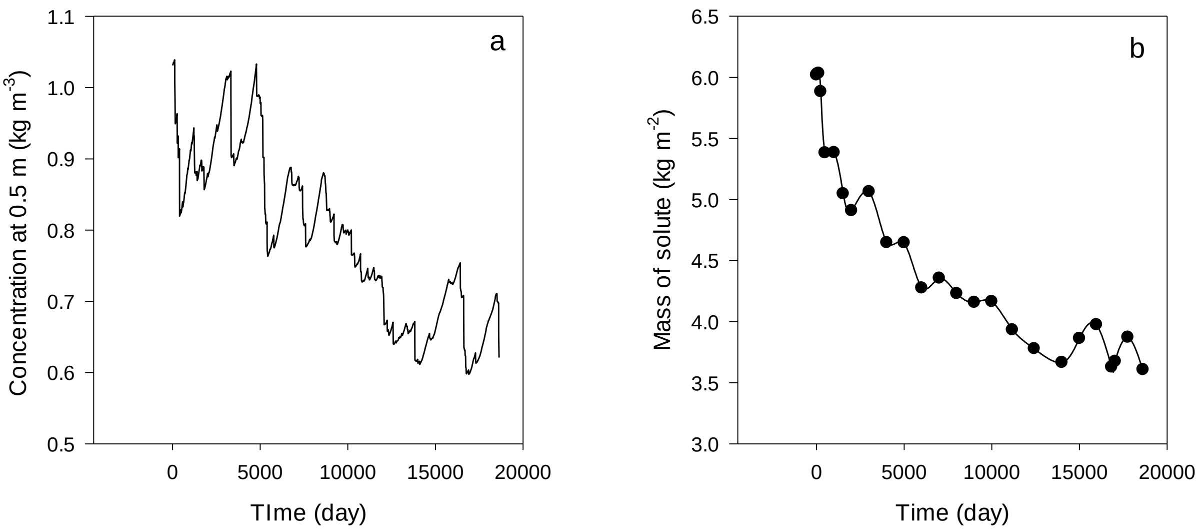

Figure 6. Scenario 1, bare soil with no irrigation, for Baseby site: a) concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.

Table 9. Water balances for the various simulation scenarios for the Baseby site for the whole 51 year simulation period: rainfall (R), irrigation (I), potential evapotranspiration (PET), simulated evaporation (E), simulated transpiration (T), simulated drainage (D), simulated runoff (RO) and the ratio of E plus T (ET) to PET. The negative values for D indicate flow to the water table and the positive values upward flow from the water table. The average irrigation volume per hectare per year ($I_{average}$) is also shown in ML ha^{-1} yr^{-1} (i.e. total I in mm divided by 5100 as simulation was over 51 years with 100 mm irrigation = 1 ML ha^{-1}).

Scenario	Water Balance Components								
	R mm	**I** mm	**$I_{average}$** ML ha^{-1} yr^{-1}	**PET** mm	**E** mm	**T** mm	**D** mm	**RO** mm	**ET/PET**
1	14949	0	0	82055	12501	0	-2504	0	0.152
2	14949	0	0	82055	7088	13660	5738	0	0.253
3	14949	67050	13.14	82055	11874	51520	-18739	0	0.773
4	14949	32200	6.31	82055	8933	44925	6969	0	0.656
5	14949	32200	6.31	82055	11222	46580	10682	0	0.661
7	14949	27200	5.33	82055	7506	41735	7258	0	0.600

In Scenario 2, the final concentration of salt at 0.5 m is high (approx. 27 kg m^{-3}, Figure 7a) which would using equation (4) result in no pasture growth and probably death of the pasture. The HYDRUS model though shows that the transpiration ratio is 0.253 (Table 9), which would indicate that some transpiration would take place after rainfall had reduced the salt concentration in the root zone. However, this assumes that a full pasture cover is still existing which is highly unlikely. The mass of salt in the soil profile is still simulated to be increasing if only slightly after 51 years (Figure 7b). These simulations do not account for precipitation of salts (e.g. gypsum) which would be likely to occur at these high concentrations.

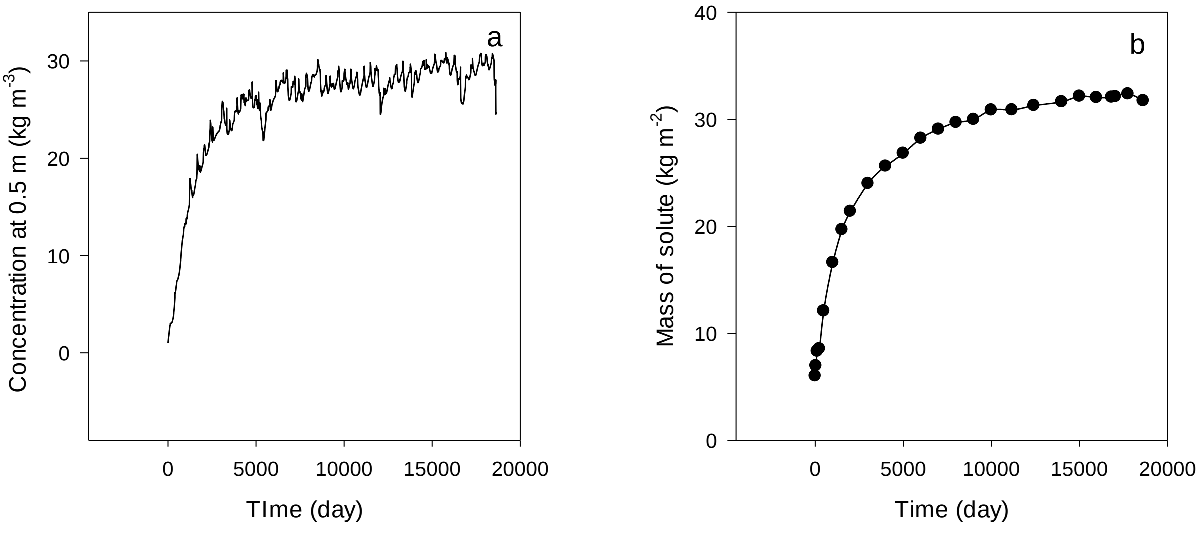

Figure 7. Scenario 2, pasture with no irrigation for Baseby site: a) salt concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

The reason that the salt accumulates in the soil profile in Scenario 2 is that upward movement of water from the water table is simulated to meet evaporation and especially transpiration. The mass of salt accumulated in in the soil is the greatest for this scenario (Table 10).

Table 10. Mass of salt initially and finally in the soil after 51 years of simulation and the source of the salt for all the scenarios for the Baseby site.

Scenario	Mass of Salt in Soil (kg m^{-2})		Source of Salt (kg m^{-2})	
	Initial	Final	Water Table	Surface
1	6.02	3.61	-3.31	9.0
2	6.02	31.74	24.60	11.1
3	6.02	4.75	-13.20	11.93
4	6.02	19.66	7.34	6.30
5	6.02	23.17	10.84	6.31
7	6.02	18.22	6.85	5.53

Scenario 3, which is based on the meteorological water deficit of -100 mm as the trigger, resulted in the most water applied (Table 9). Salinity decreased from the initial values (Figure 8) to reach a steady state at approximately 1 kg m^{-3}, with similar trends and final salinities to Scenario 1 (Table 10). This scenario used large volumes of water, 13.14 ML/ha which is similar to the volumes calculated for maximum pasture growth in section 2 of this report (13.42 ML/ha).

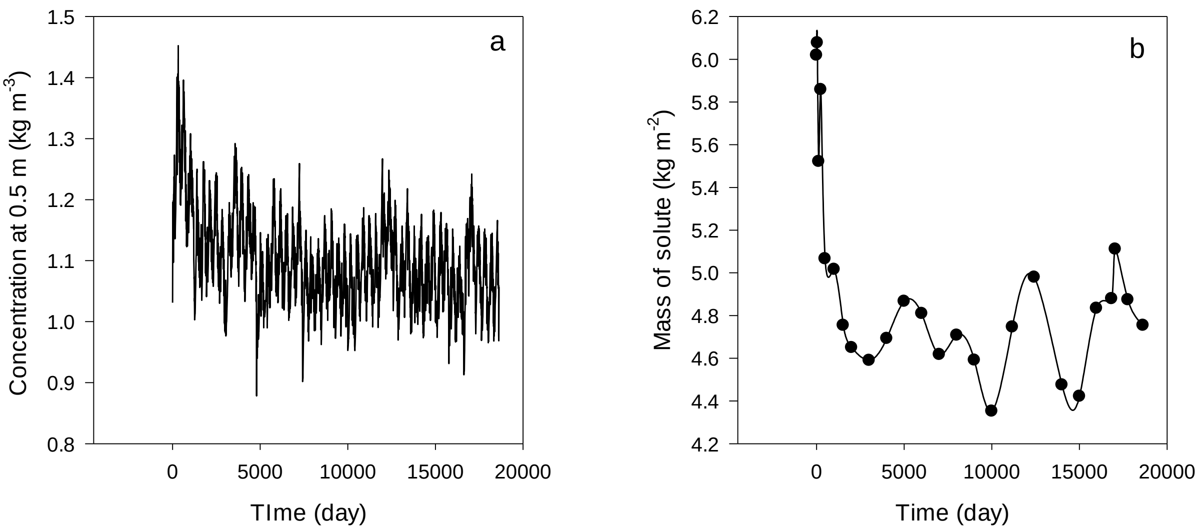

Figure 8. Scenario 3, 100 mm irrigation when a 100 mm potential water deficit occurred at the Baseby site: a) salt concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

Scenarios 4 and 5 used volumes equivalent to the specific ELMA rate for Baseby and show that the salt concentration at 0.5 m builds up in the first 10 years of simulation and becomes stable at approximately 14−17 kg m^{-3} (Figure 9 and Figure 10). While the salt concentration builds up in the soil profile, the combination of rainfall and irrigation should allow for the pasture to survive as indicated by transpiration ratio of 0.66. This should allow the land to be able to recover when full irrigation like Scenario 3 resumes following a drought period.

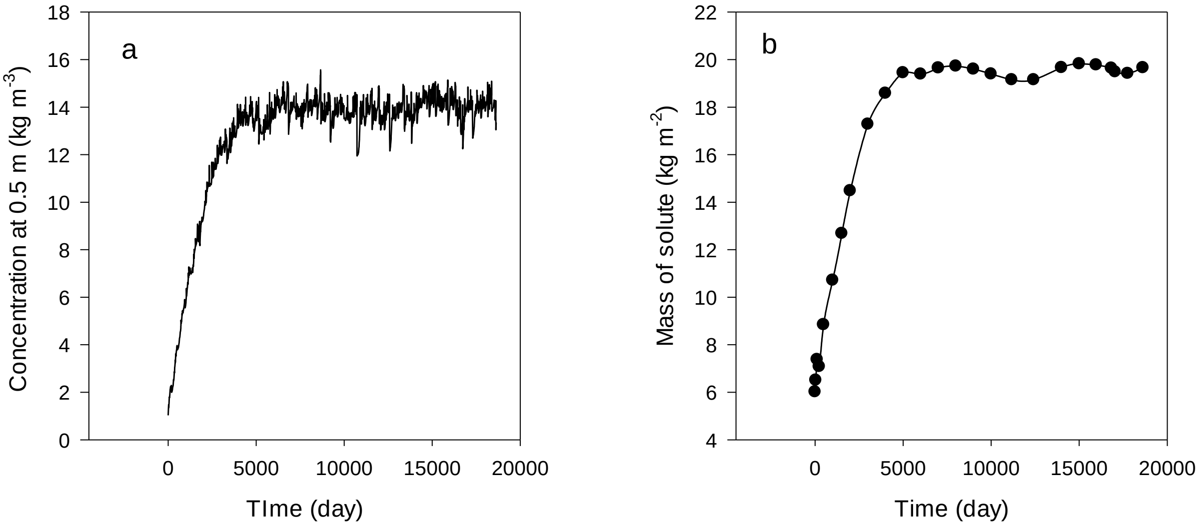

Figure 9. Scenario 4, pasture with irrigation of volumes equivalent to ELMA for Baseby site with 100 mm irrigations: a) concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.

What we can also observe from comparing these two scenarios is application of a lower amount of water more frequently in Scenario 5 was less effective at keeping the salt concentration down and reducing the mass stored in the soil profile than in Scenario 4. From equations 4 and 5 we can calculate that the maximum EC before transpiration and hence yield was reduced to zero is 35 kg m^{-3}). The similar ET/PET ratio indicates that little difference in pasture growth and cover on the soil surface is likely with either scenario 4 or 5.

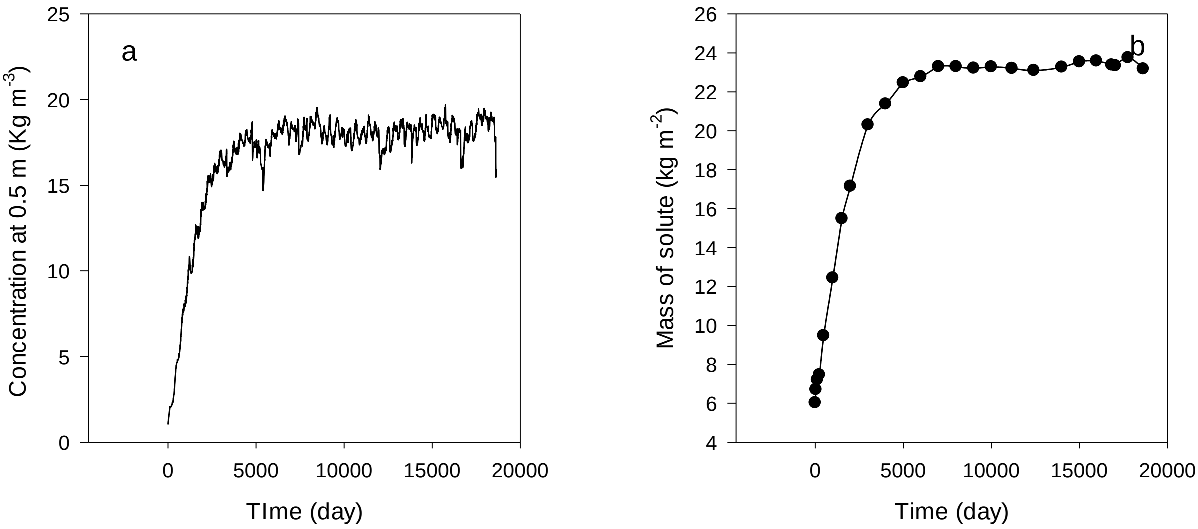

Figure 10. Scenario 5, pasture with irrigation of volumes equivalent to ELMA for Baseby site with irrigation at scenario 3 time intervals and irrigations of 48 mm: a) concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.

This leads to the strategy used in Scenario 7 where the timing of the irrigation was based on the salt threshold concentration at 0.5 m and irrigation amounts of 200 mm. This scenario resulted in the final salt concentration and mass being maintained (Figure 11) at values slightly less than that of Scenarios 4 and 5, even though the total irrigation volume applied was less (Table 9).

The salt concentration at 0.5 m has a much greater fluctuation about the steady state than the other strategies due to the larger irrigation amount of 200 mm. This also results in the root zone being more salty for longer which means that the transpiration ratio is 0.6 compared to 0.66 for Scenarios 4 and 5. It may still result in slightly poorer pasture growth than for Scenarios 4 and 5 but it also uses less water.

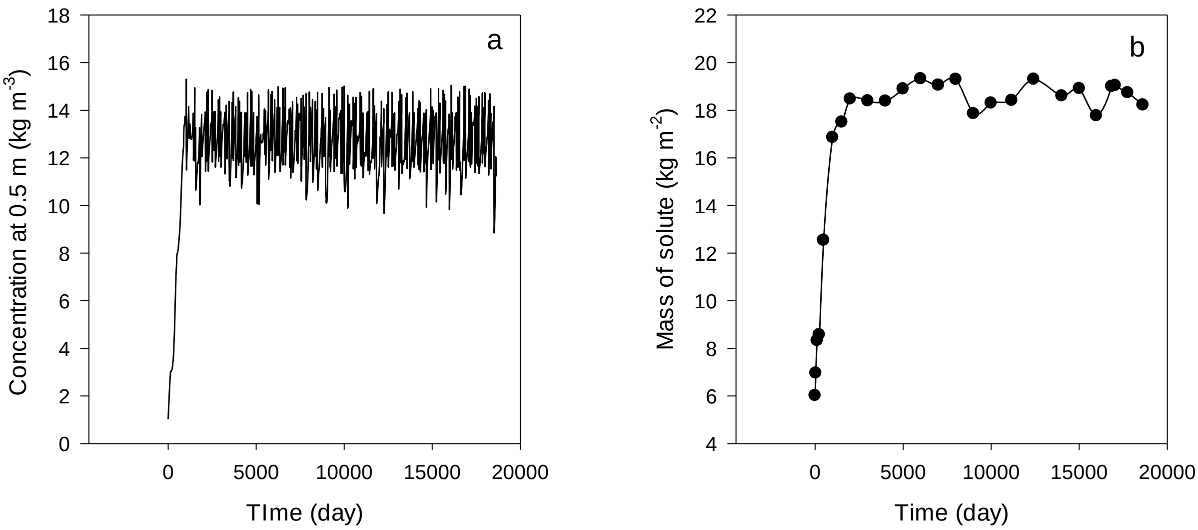

Figure 11. Scenario 7, pasture with irrigation for Baseby site triggered by salt concentration at 0.5 m depth: a) salt concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.

The above outputs only look at the salt concentration at the bottom of the rootzone. To better understand the dynamic nature of the salt concentration throughout the rootzone, a subregion for the rootzone was introduced in the HYDRUS1D domain. This allows the mass of salt ($SM_r(t)$ (kg m^{-2})) within the rootzone to be monitored. The volume of water per unit area within the rootzone at saturation can also be calculated (W_r (m^3 m^{-2}) and mean concentration at saturation of the rootzone calculated by:

$$\bar{C}_r = SM_r(t) / W_r \qquad (8)$$

From eqn (8) and eqn (5) the mean EC_{se} of the rootzone can be calculated and compared with the threshold, R = 0.5 and R = 0, EC_{se} values (Figure 12). When compared to Figure 11a uncorrected modelled salinity values, the EC_{se} corrected Figure 12 results show a much wider range of values because it is a mean over the whole rootzone not a point at the bottom of the rootzone. Figure 12 also indicates that the mean EC_{se} never rises above the point at which transpiration would cease and that it mostly varies around the point where the transpiration would be reduced by 50%. However, following irrigation it drops below the threshold value. This is also a mean value across the whole rootzone mean that there will be area within the rootzone where the concentration is less than the mean value and water uptake will occur preferentially from these areas. Thus, we would expect the reduction in transpiration compared to PET to be less than 50% for this scenario which is confirmed by the results in Table 9, where the reduction is 40%. Given that yield is highly correlated with transpiration we would also expect a similar 40% reduction in yield. Even if the lower 50% reduction (12.2 dS m^{-1}) and 100% reduction (18.8 dS m^{-1}) values for EC*se* from FAO (2002) were used the results would still suggest that the yield reduction will be in the range of 50-60%. This suggest that scenario 7 can result in sustaining the rye grass while using less water than is presently allocated with ELMA at this site.

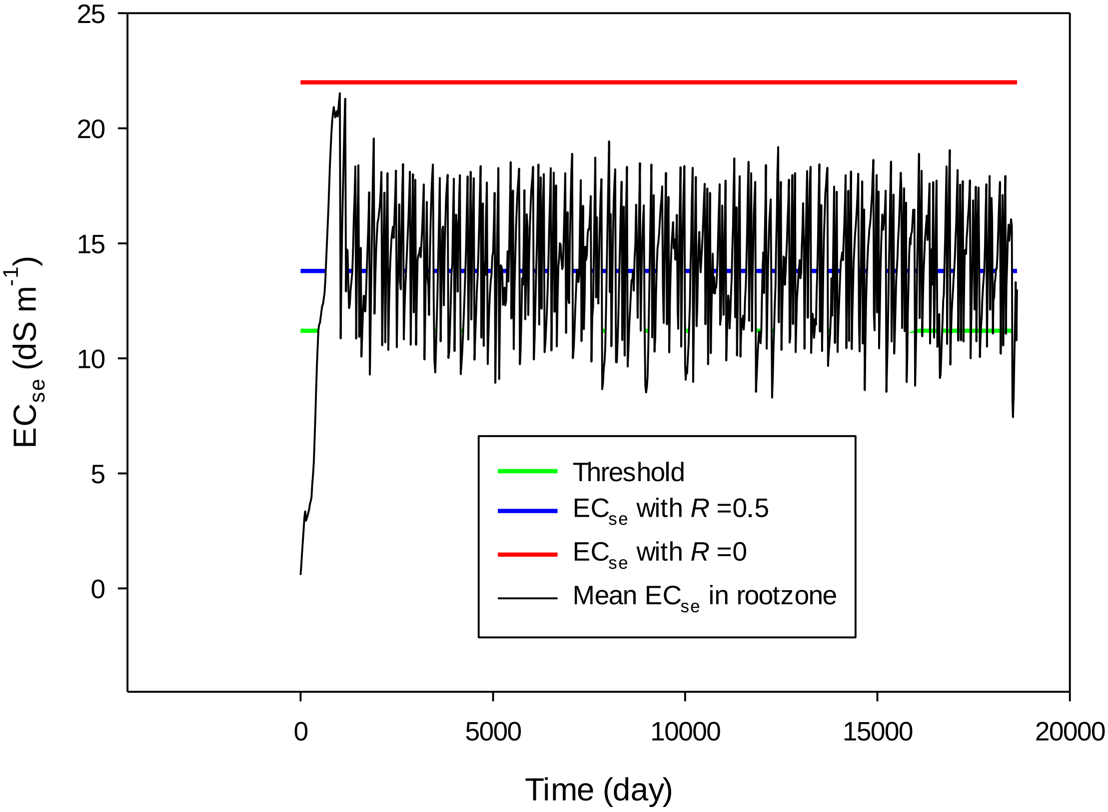

Figure 12 Mean EC_{se} in the rootzone calculated with eqn (8) for Baseby compared with the threshold value and estimated EC_{se} values when R = 0.5 (EC_{se} = 13.8 dS m^{-1}) and R = 0 (EC_{se} = 22 dS m^{-1}).

The bottom cumulative salt mass transfer from the water table, after an initial sharp rise before irrigations start, the mass decreases slightly with time (Figure 13). This indicates the beneficial effects of irrigation in suppressing the upward salt transport. It is likely the cumulative solute mass starts to decline after a peak at about 10 years due to the higher root zone salinity limiting transpiration.

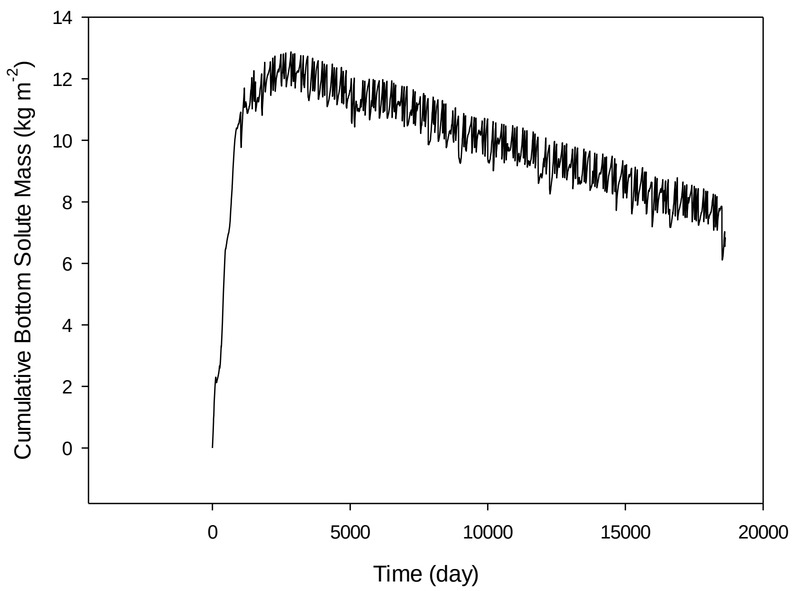

Figure 13 Cumulative salt mass in the water table with time for Scenario 7 for the Baseby site.

The pasture performance is likely to be reduced as indicated by the transpiration which is 41,735 mm compared to 51,520 mm for Scenario 3 (Table 9). This would suggest that since the amount of plant production is strongly linked to transpiration that pasture growth would be 81% of that with scenario 3. This could be achieved with 5.33 ML ha^{-1} yr^{-1} compared with 6.31 ML ha^{-1} yr^{-1} which is currently available as ELMA, equating to a water saving of 1 ML ha^{-1} yr^{-1}.

The overall drainage values show that only Scenario 1 and Scenario 3 result in a net drainage of water from the soil profile of 17% and 22% respectively while all the other scenarios result in a net upward movement of water (Table 9). To see how the ELMA allocations compared to the leaching fraction drainage requirement, the bottom boundary condition was also changed to free drainage in the simulations. These results (not shown) confirmed that the shallow saline groundwater table is the main source of salt and driver of soil salinisation.

4.6.2 Long Flat

The Long Flat site was used to represent the middle region of the LMRIA. The bare soil simulation (Scenario 1) showed that the concentration of salt at the base of the root zone (0.5 m depth) would decrease with time as would the total mass (Figure 14). This occurs because the soil surface dries and evaporation decreases below the PET, so that when rain occurs it results in drainage from the soil profile. This loss has almost reached steady state by the end of the simulation. This may not be realistic and recent field trials with bare soil showed land salinization occurred quite quickly without irrigation on bare soil and salt tolerant vegetation establishes in the absence of pasture (Mosley et al. 2017a).

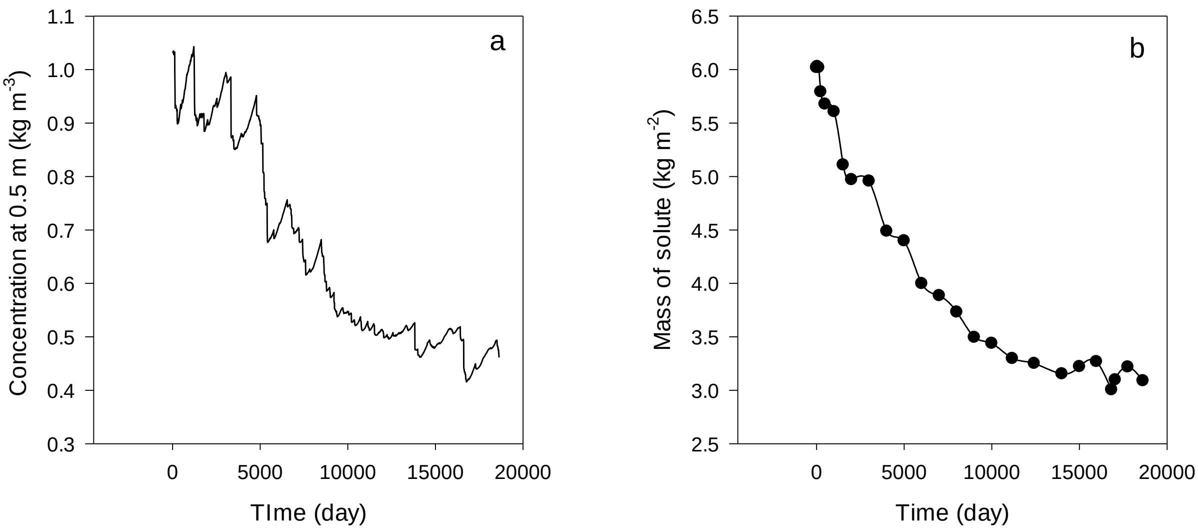

Figure 14 Scenario 1, bare soil with no irrigation, for Long Flat site: a) concentration at 0.5 m depth and total salt mass in soil to a depth of 3 m.

The ratio of ET/PET (in this case only E to PET as bare soil) was low at 0.184, which is why in this case the rainfall can flush the salt from the soil (Table 11).

Table 11. Water balances for the various simulation scenarios for the Long Flat site: rainfall (R), irrigation (I), potential evapotranspiration (PET), simulated evaporation (E), simulated transpiration (T), simulated drainage (D), simulated runoff (RO) and the ratio of E plus T (ET) to PET. The negative values for D indicate flow to the water table and the positive values upward flow from the water table. Irrigation is also shown in ML ha^{-1} yr^{-1} (i.e. total I in mm divided by 5100 as simulation was over 51 years with 100 mm irrigation = 1 ML ha^{-1}).

Scenario	**Water Balance Components**								
	R mm	**I** mm	**$I_{average}$** ML ha^{-1} yr^{-1}	**PET** mm	**E** mm	**T** mm	**D** mm	**RO** mm	**ET/PET**
1	18086	0	0	80074	14752	0	-3305	0	0.184
2	18086	0	0	80074	7760	16312	6032	0	0.301
3	18086	61900	12.13	80074	12167	50593	-17490	0	0.784
4	18086	22200	4.31	80074	9023	38717	7597	0	0.596
5	18086	22300	4.31	80074	11967	35002	6574	0	0.587
7	18086	24600	4.82	80074	8100	41499	7067	0	0.619

When pasture is added with no irrigation (Scenario 2) the salt does build up (Figure 15 Scenario 2, pasture with no irrigation for Long Flat site: a) concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.a) in the soil and with the concentration at 0.5 m rising to almost 30 kg m^{-3} , which is close to the point (35.28 kg m^{-3}) at which transpiration and hence plant growth will cease (Figure 15a). This would most likely result in death of the pasture in many areas. The mass of salt in the soil profile is still simulated to be increasing, if only slightly, after 51 years (Figure 15b). The amount is also similar to that for the Baseby site as the salt supresses the transpiration and hence the upward flux of water from the water table reduces.

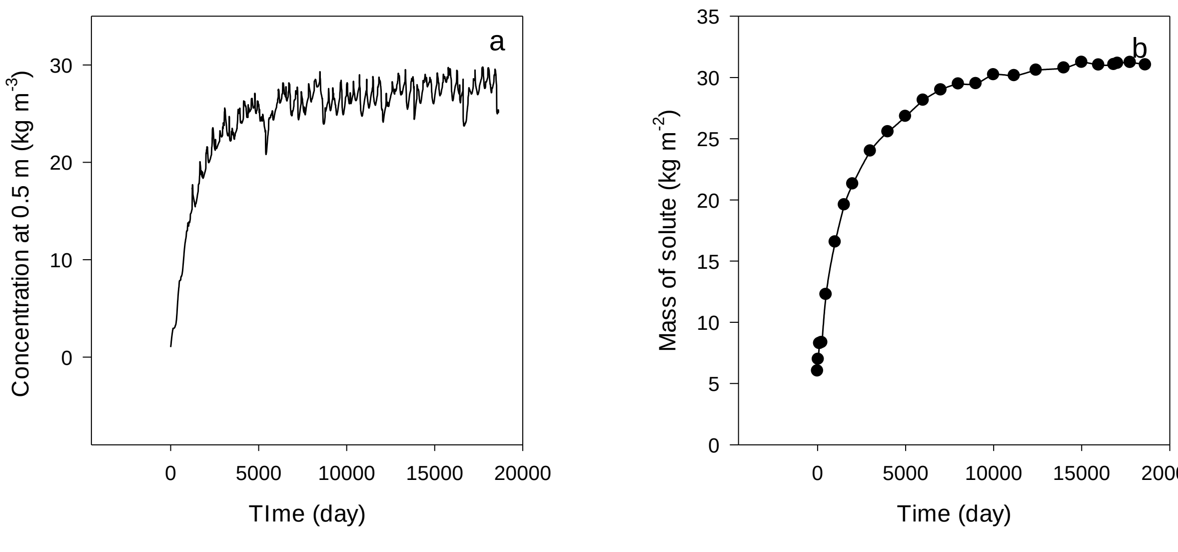

Figure 15 Scenario 2, pasture with no irrigation for Long Flat site: a) concentration at 0.5 m depth and (b) total salt mass in soil to a depth of 3 m.

Due to this site having less of a water deficit the concentration and accumulated mass of salt in the soil is slightly less than that for the Baseby site. The reason that the salt accumulates in the soil profile in Scenario 2 is that upward movement of water from the water table is simulated to meet evaporation and especially transpiration. The mass of salt accumulated in in the soil is the greatest for this scenario (Irrigation with Scenario 3, which was based on the meteorological water deficit of -100 mm as the trigger, resulted in salinity decreasing during the simulation (Figure 16). This scenario had the most water applied (12.13 ML ha^{-1} yr^{-1}) and had a similar soil salinity at the end of the 51 years simulation as Scenario 1 (Table 12). The amount of water applied was approximately three times that of the ELMA for this site and similar to the volume calculated for maximum crop growth (12.38 ML ha^{-1} yr^{-1}).

Irrigation with Scenario 3, which was based on the meteorological water deficit of -100 mm as the trigger, resulted in salinity decreasing during the simulation (Figure 16). This scenario had the most water applied (12.13 ML ha^{-1} yr^{-1}) and had a similar soil salinity at the end of the 51 years simulation as Scenario 1 (Table 12). The amount of water applied was approximately three times that of the ELMA for this site and similar to the volume calculated for maximum crop growth (12.38 ML ha^{-1} yr^{-1}).

Table 12 Mass of salt initially and finally in the soil after 51 years of simulation and the source of the salt for all the scenarios for the Long Flat site.

Scenario	Mass of Salt in Soil (kg m^{-2})		Source of Salt (kg m^{-2})	
	Initial	Final	Water Table	Surface
1	6.02	3.09	-4.03	1.10
2	6.02	31.02	23.65	1.35
3	6.02	4.76	-12.59	11.33
4	6.02	22.59	11.64	4.93
5	6.02	26.44	15.47	4.94
7	6.02	19.06	81.32	5.31

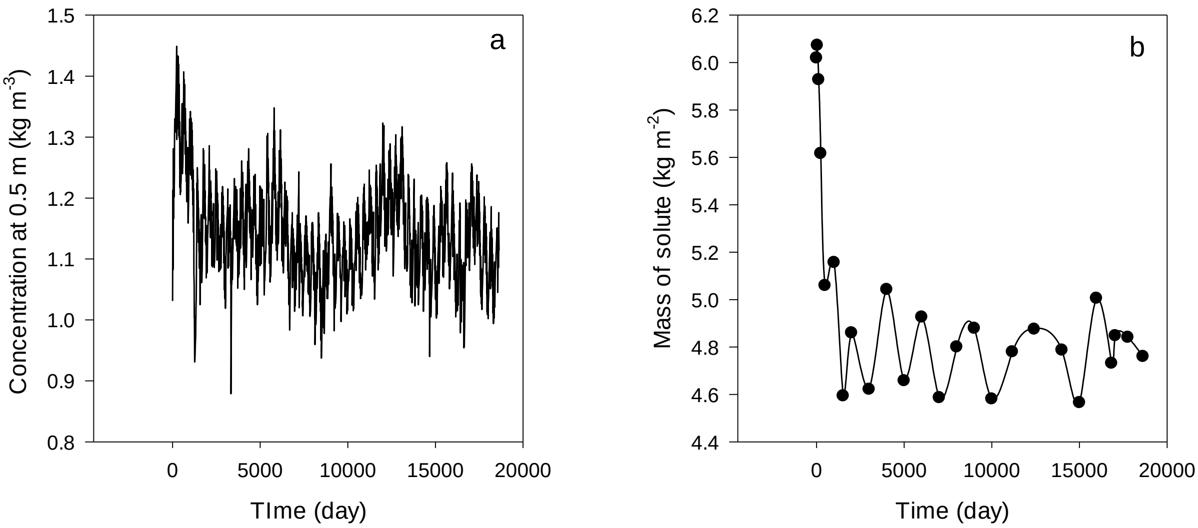

Figure 16 Scenario 3, 100 mm irrigation when a 100 mm potential water deficit occurred at the Long Flat site: a) salt concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

Scenarios 4 and 5 use the ELMA rate for Long Flat and show that salt builds up in the first 10 years of simulation and becomes stable at approximately 17–24 kg m^{-3} (Figure 17 and Figure 18). The steady state concentration for scenario 4 is less than the value at which the transpiration would be reduced by 50% (22 kg m^{-3}) in equation (4) in Scenario 4, so transpiration would expect to be reduced by less than 50% (Table 11 shows a reduction of about 40% in transpiration). Similarly pasture growth would be expected to also decline by a similar amount. Scenario 5 shows salt concentrations at 0.5 m on occasion are above the 50% transpiration reduction limit. Thus, we would expect a similar to slightly greater reduction in transpiration than for Scenario 4. This is shown in Table 11. The pasture yield would be expected to reduce by about 40% compared to the potential yield, but fluctuates more widely than Scenario 4. The salt mass at the end of the simulation for scenarios 4 and 5 at the Long

Flat site was approximately 2-3 kg m^{-2} respectively higher than for the Baseby site (compare Table 10 and Table 12). The greater salt mass and higher concentration is due to the lower ELMA for the Long Flat site compared to the Baseby site.

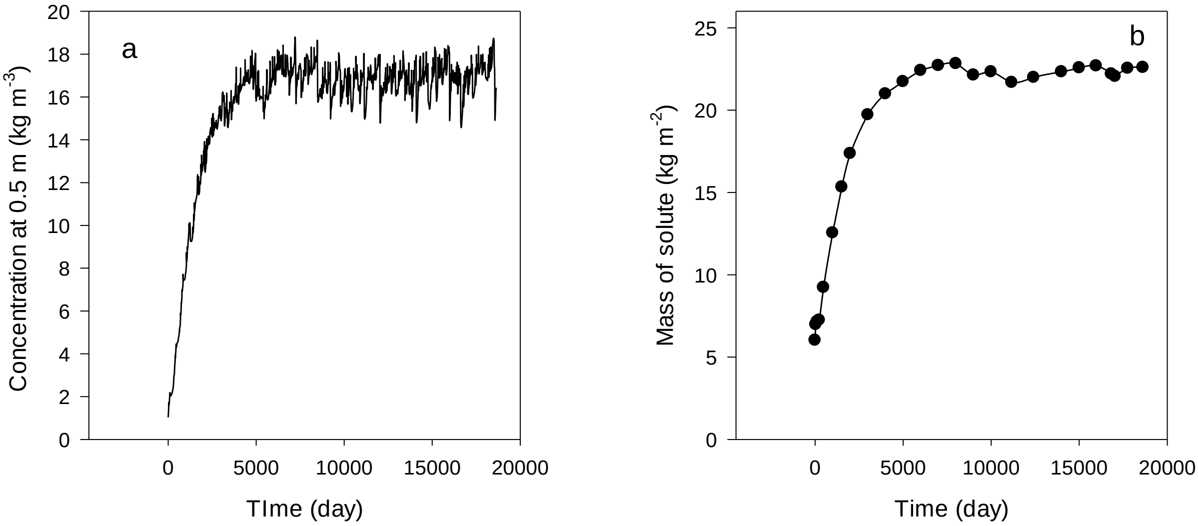

Figure 17 Scenario 4, pasture with ELMA irrigation for Long Flat site with 100 mm irrigations: a) concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

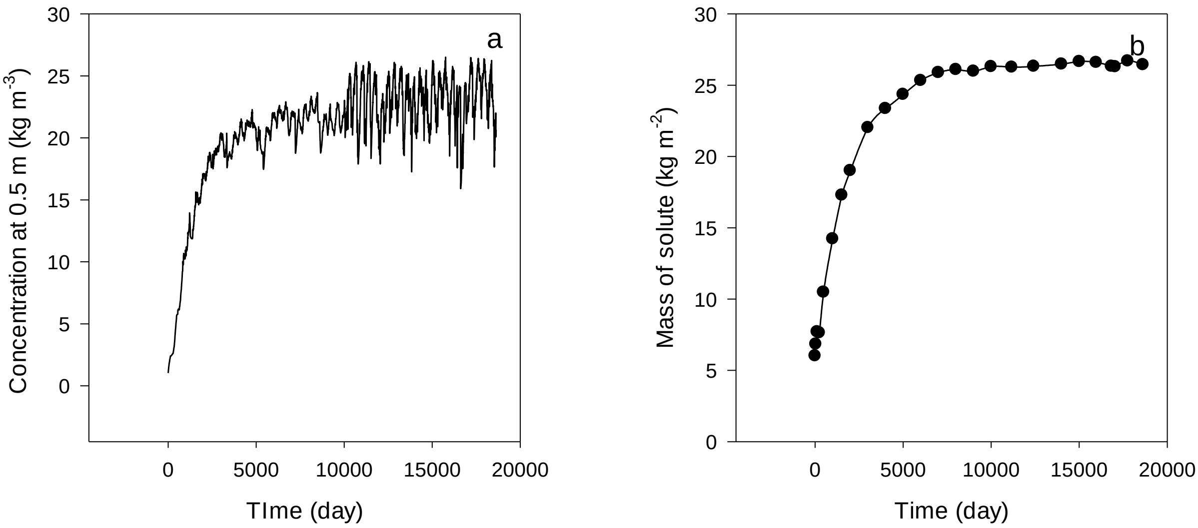

Figure 18 Scenario 5, pasture with ELMA irrigation for Long Flat site with irrigation at scenario 3 time intervals and irrigations of 48 mm: a) concentration at 0.5 m depth and total salt mass in soil to a depth of 3 m.

Scenario 7 showed that the salt concentration and mass can be maintained at approximately 13.9 kg m^{-3} (Figure 19) compared to 14-18 and 20-25 kg m^{-3} in Scenarios 4 and 5 respectively. The mean annual irrigation required for this scenario over the last 41 years of the simulation was 5.21 ML ha^{-1} yr^{-1}. This is greater than ELMA allocation of 4.46 ML ha^{-1} yr^{-1} by 0.75 ML ha^{-1} yr^{-1}.

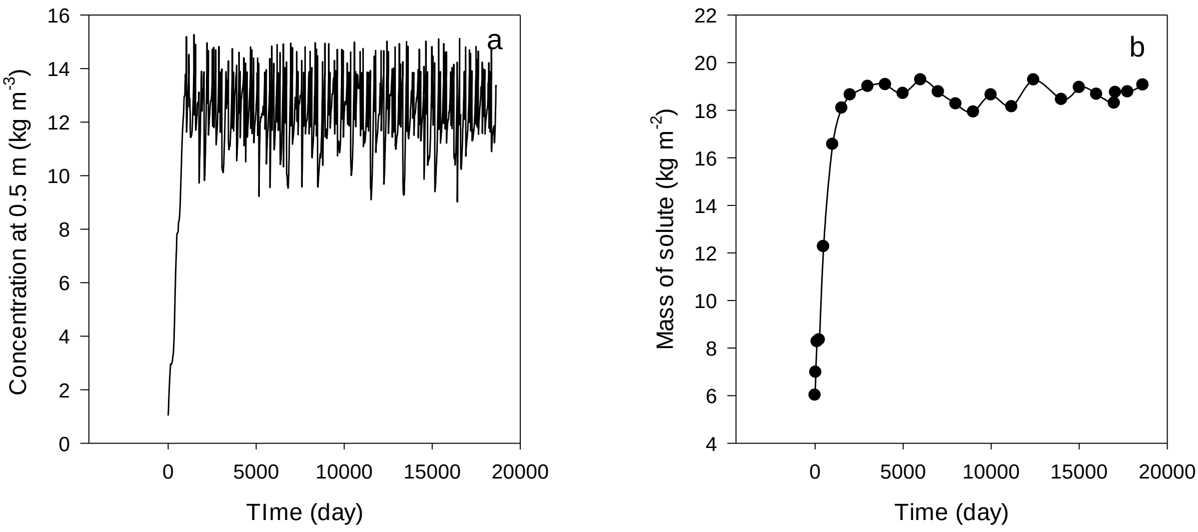

Figure 19 Scenario 7, pasture with irrigation for Long Flat site trigger by salt concentration at 0.5 m depth: a) concentration at 0.5 m depth and total salt mass in soil to a depth of 3 m.

Using the mass of salt in the rootzone the mean EC_{se} can be estimated and is compared to the threshold, $R = 0.5$ and $R = 0$ values in Figure 20. This shows that the mean EC_{se} is kept around the value associated with a 50% reduction in transpiration and always below where we would expect transpiration to cease. This is supported by the values in Table 11 where the reduction in transpiration compared to the potential rate is approximately 40%. Even if the FAO (2002) yield reduction values of 12.2 dS m^{-1} for 50% reduction and 18.8 dS m^{-1} for 100% reduction are used the results suggest that the pasture yield will still be about 50% of the potential.

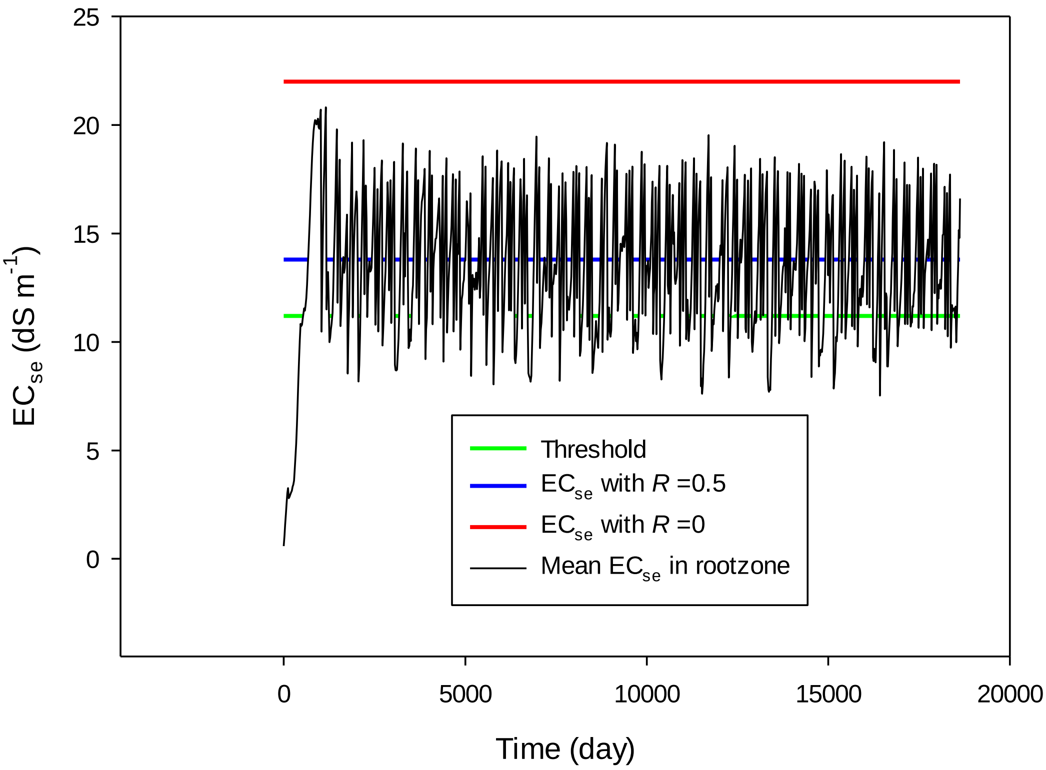

Figure 20 Mean EC_{se} in the rootzone calculate with eqn (8) at Long Flat compared with the threshold value and estimated EC_{se} values when $R = 0.5$ (EC_{se} = 13.8 dS m^{-1}) and $R = 0$ (EC_{se} = 22 dS m^{-1}).

The bottom cumulative salt mass transfer from the water table after an initial sharp rise before irrigations start then decrease slightly with time (Figure 21). This scenario uses larger single irrigations of 200 mm and slightly more water than the current ELMA allocation.

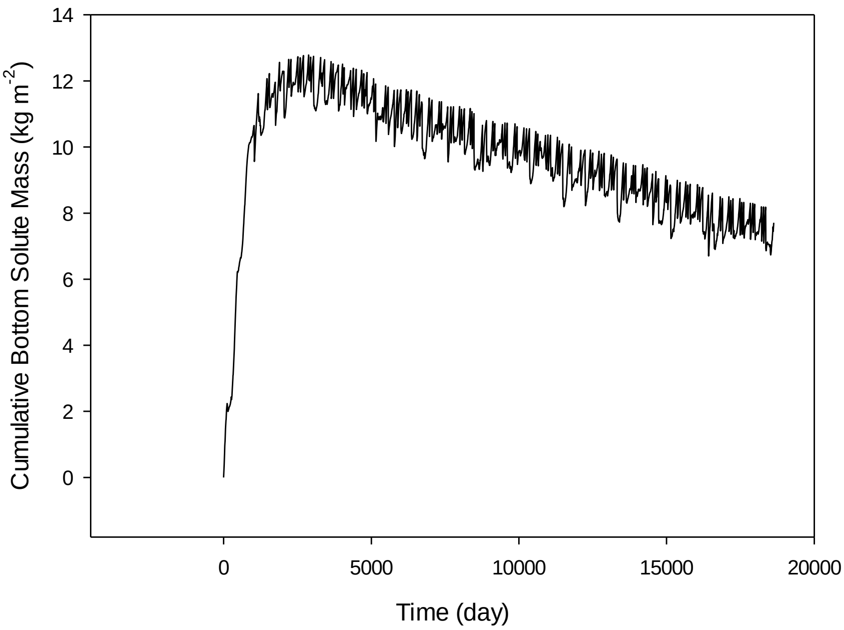

Figure 21. Cumulative salt from water table with time for scenario 7 for Long Flat site.

The transpiration for scenario 7 is 41,499 mm and scenario 3 is 50,593 mm, which is a ratio of 0.82. This means that plant growth and hence protective cover of the soil surface could be maintained with larger single irrigations, as well as maintenance of the soil condition to avoid salinization, at a rate of 5.21ML ha^{-1}. The ELMA allocations result in less transpiration compared with what would occur under Scenario 7, (ratio of 77% and 69% for scenarios 4 and 5 respectively compared to the transpiration in the well-watered scenario 3) respectively but would also still be likely to maintain pasture cover of the soil surface.

The overall drainage values show that only Scenario 1 and Scenario 3 result in a net drainage of water from the soil profile and of 18% and 22% respectively while all the other scenarios result in a net upward movement of water (Table 11).

To see how volumes equivalent to ELMA allocations compared to the leaching fraction drainage requirement, the bottom boundary condition was also changed to free drainage in the simulations. These results (not shown) confirmed that the shallow saline groundwater table is the main source of salt and driver of soil salinisation.

4.6.3 Jervois

The Jervois site was used to represent the southern region of the LMRIA. The bare soil simulation (Scenario 1) showed that the concentration at the base of the root zone (0.5 m depth) would decrease with time as would the total mass (Figure 22). This occurs because the soil surface dries and evaporation decreases below the PET, so that when rain occurs it results in drainage from the soil profile. This loss has reached steady state by about 10,000 days of the simulation. The ratio of ET/PET (in this case only E to PET as bare soil) is low at 0.185, which is why in this case the rainfall can flush the salt from the soil. This may not be realistic as salt tolerant vegetation establishes in the absence of pasture and recent field trials with bare soil showed land salinization occurred quite quickly without irrigation on bare soil (Mosley et al. 2017a).

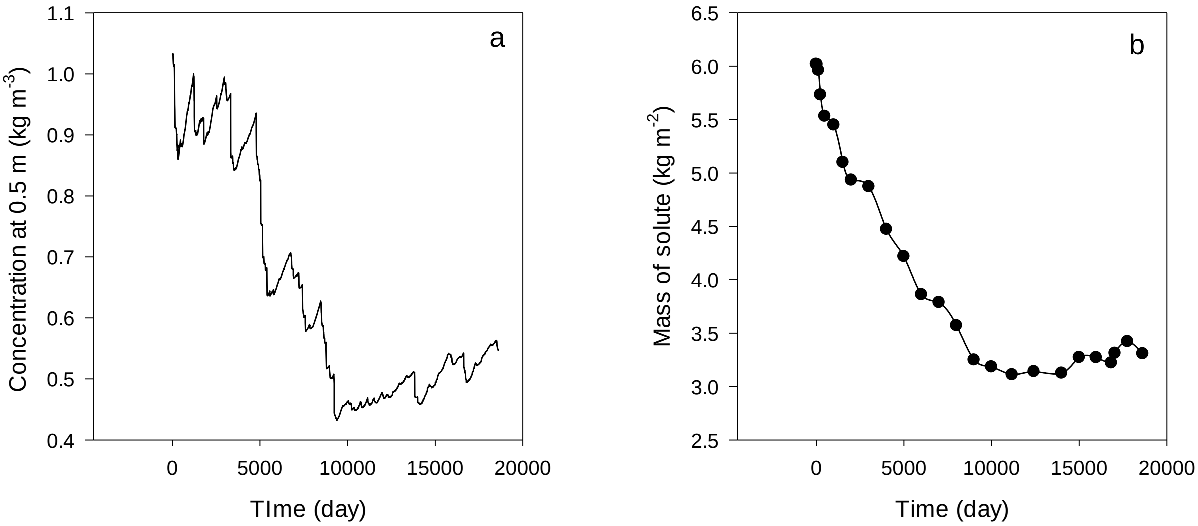

Figure 22 Scenario 1, bare soil with no irrigation, for Jervois site: a) concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m. Due to the higher amount of water applied in scenario 3 and smaller actual evaporation in scenario 1, these are the only scenarios where leaching of salt back to the water table occurs.

Table 13. Water balances for the various simulation scenarios for the Jervois site: rainfall (R), irrigation (I), potential evapotranspiration (PET), simulated evaporation (E), simulated transpiration (T), simulated drainage (D), simulated runoff (RO) and the ratio of E plus T (ET) to PET. The negative values for D indicate flow to the water table and the positive values upward flow from the water table. Irrigation is also shown in ML ha^{-1} yr^{-1} (i.e. total I in mm divided by 5100 as simulation was over 51 years with 100 mm irrigation = 1 ML ha^{-1}).

Scenario	**Water Balance Components**								
	R mm	**I** mm	**$I_{average}$** ML ha^{-1} yr^{-1}	**PET** mm	**E** mm	**T** mm	**D** mm	**RO** mm	**ET/PET**
1	18260	0	0	80664	14922	0	-3311	0	0.185
2	18260	0	0	80664	7639	20285	9731	0	0.346
3	18260	62350	12.22	80664	12252	50946	-17570	0	0.783
4	18260	14800	2.90	80664	8344	36462	11985	0	0.555
5	18260	14800	2.90	80664	12137	30736	9793	0	0.532
7	18260	24600	4.82	80664	7431	41812	7059	0	0.652

When pasture is added with no irrigation (Scenario 2) the salt does build up (Figure 23a) in the soil and with the concentration at 0.5 m rising to close to 30 kg m^{-3}. The salt concentration above this will go to higher concentrations between rainfall events, which is likely to result in death of the pasture. The mass of salt in the soil profile is still simulated to be increasing if only slightly after 51 years (Figure 23b).

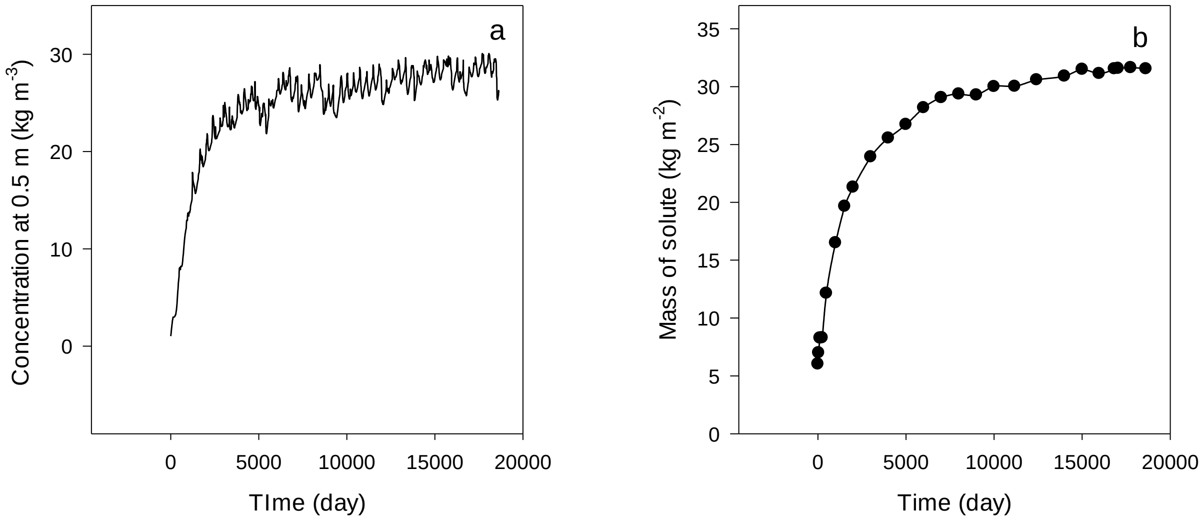

Figure 23 Scenario 2, pasture with no irrigation for Long Flat site: a) concentration at 0.5 m depth and total salt mass in soil to a depth of 3 m.

Although Jervois has less of a water deficit than the Long Flat site (due to higher rainfall primarily) the concentration and accumulated mass of salt in the soil is about the same. The reason that the salt accumulates in the soil profile is that upward movement of water from the water table is simulated to meet evaporation and especially transpiration. The mass of salt accumulated in in the soil is the greatest for this scenario (Table 14).

Table 14. Mass of salt initially and finally in the soil after 51 years of simulation and the source of the salt for all the scenarios for the Jervois site.

Scenario	**Mass of Salt in Soil (kg m^{-2})**		**Source of Salt (kg m^{-2})**	
	Initial	Final	Water Table	Surface
1	6.02	3.31	-3.86	1.15
2	6.02	31.55	24.13	1.38
3	6.02	4.30	-4.83	3.11
4	6.02	25.72	15.93	3.76
5	6.02	29.63	19.83	3.77
7	6.02	18.72	9.99	2.63

Irrigation in Scenario 3, which is based on the meteorological water deficit of -100 mm as the trigger, resulted in salinity decreasing during the simulation (Figure 24). This Scenario had the most water applied (12.22 ML ha^{-1}), similar to the volumes indicated for maximum pasture growth in section 2 (12.48 ML/ha) and approximately four times that of the ELMA for this site (Table 13).

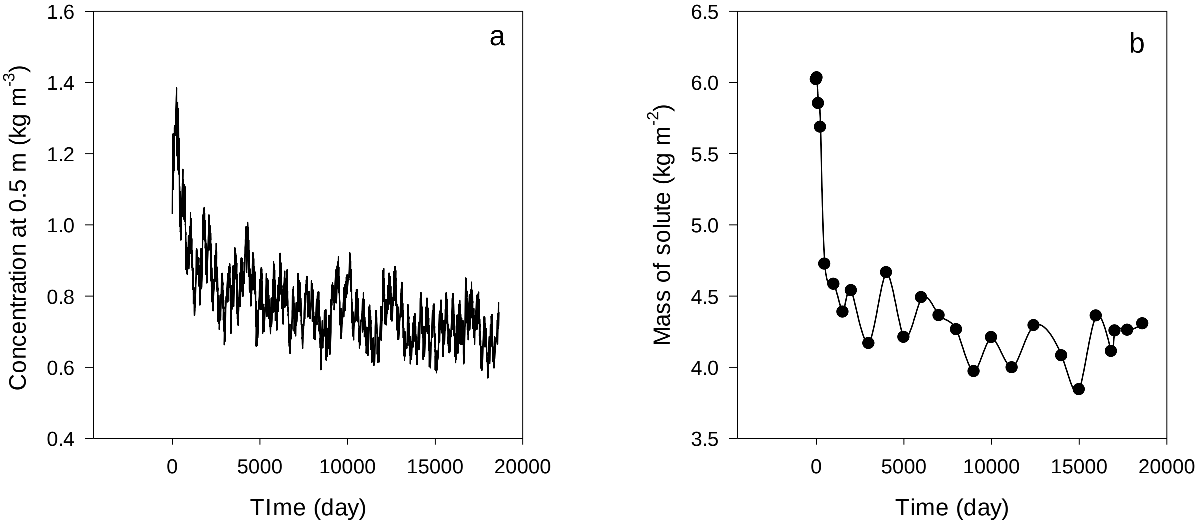

Figure 24 Scenario 3, 100 mm irrigation when a 100 mm potential water deficit occurred at the Jervois site: a) salt concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

Scenarios 4 and 5 only applied the ELMA and showed that that salt builds up in the first 10 years of simulation and becomes stable at approximately 20 kg m^{-3} (Figure 25 and Figure 26). The steady state concentration at 0.5 m depth for scenario 4 at the Jervois site (Figure 25) is approximately 20 kg m^{-3} which is close to the value at which a reduction of 50% in transpiration would occur using equation (4 This is likely to result in about a 50% reduction in pasture yield and may result in some bare patches in the pasture due to variation in soil properties. The steady state concentration at 0.5 m depth for scenario 5 at the Jervois site (6) is approximately 21−22 kg m^{-3} this is again at the value for a 50% reduction in the transpiration from equation (4) and would pasture yield will be reduced by a similar amount. The steady state concentrations for these two scenarios are greater than for the Baseby and Jervois site due to the allocation of water in the ELMA being lower. The reductions in transpiration from the simulations are around 45% in line with the expectation from equation (4). Although pasture growth is likely to be maintained with these scenarios there is a higher risk of pasture death and bare soil leading to erosion.

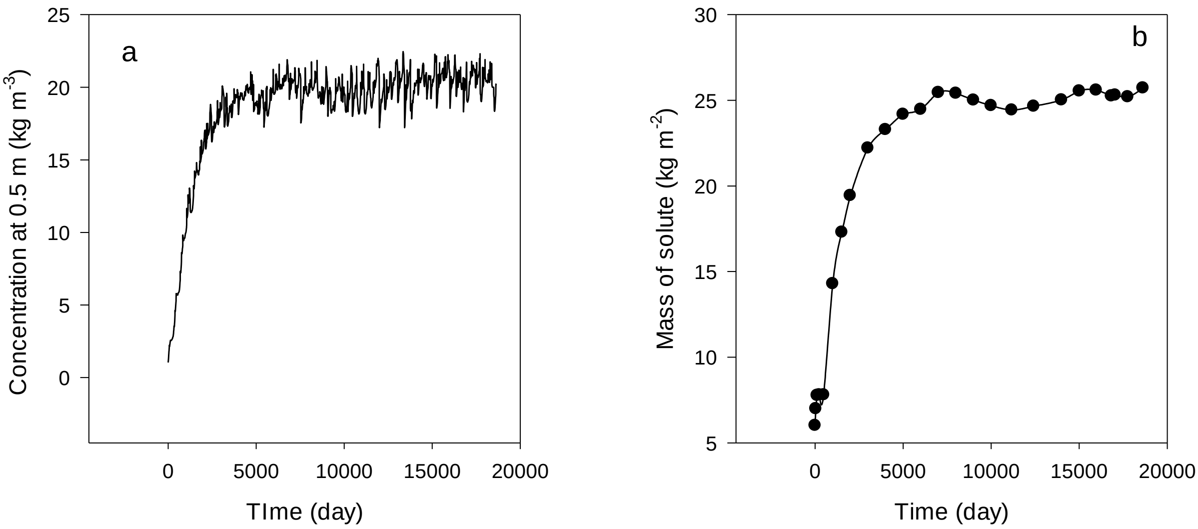

Figure 25 Scenario 4, pasture with ELMA irrigation for the Jervois site with 100 mm irrigations: a) concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

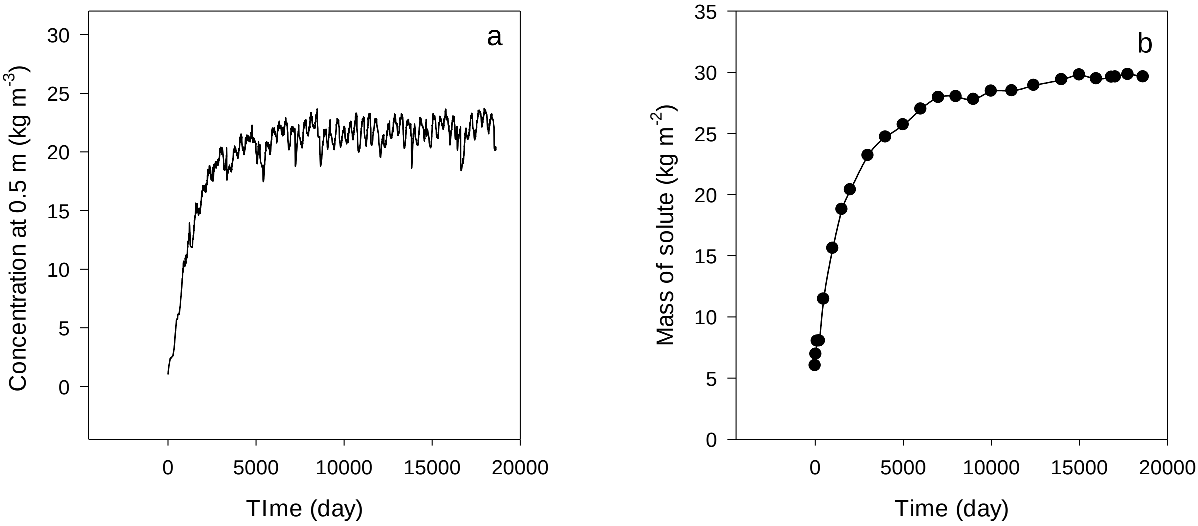

Figure 26 Scenario 5, pasture with ELMA irrigation for Long Flat site with irrigation at scenario 3 time intervals and irrigations of 48 mm: a) concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

Scenario 7 showed that the salt concentration and mass can be maintained at approximately 13.9 kg m^{-3} and 18 kg m^{-2} respectively (Figure 27). The mean annual irrigation required for this scenario over the last 41 years of the Jervois simulation was 5.21 ML ha^{-1} yr^{-1}. This is greater than ELMA allocation of 2.96 ML ha^{-1} yr^{-1} by 2.32 ML ha^{-1} yr^{-1}.

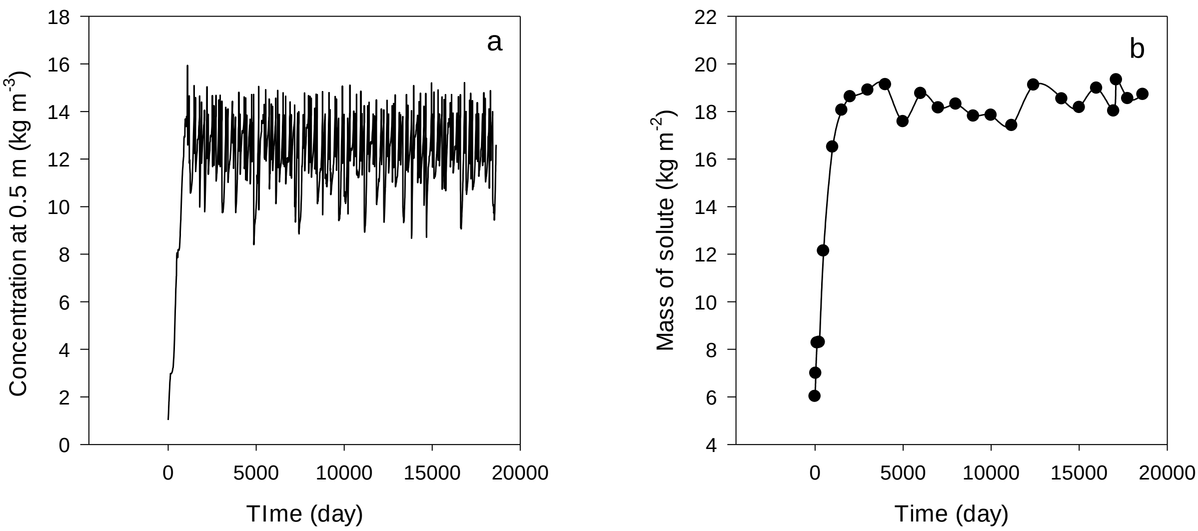

Figure 27 Scenario 7, pasture with irrigation for the Jervois site trigger by salt concentration at 0.5 m depth: a) concentration at 0.5 m depth and b) total salt mass in soil to a depth of 3 m.

Using the mass of salt in the rootzone the mean EC_{se} can be estimated and is compared to the threshold, R = 0.5 and R = 0 values in Figure 28. This shows that the mean EC_{se} is kept around or less than the value associated with a 50% reduction in transpiration and always below where we would expect transpiration to cease. This is supported by the values in Table 13 where the reduction in transpiration compared to the potential rate is approximately 35%. The mean EC_{se} value stays below the threshold line for longer at this site compared to the Baseby and Long Flat sites which is possibly why the reduction in transpiration is less. Similarly if the FAO (2002) values for yield reduction were used the yield reduction is likely to be around 50%.

The bottom cumulative salt mass transfer from the water table after an initial sharp rise before irrigations start then decreases slightly with time (Figure 29). This scenario uses larger single irrigations of 200 mm and almost double the water than the ELMA at Jervois.

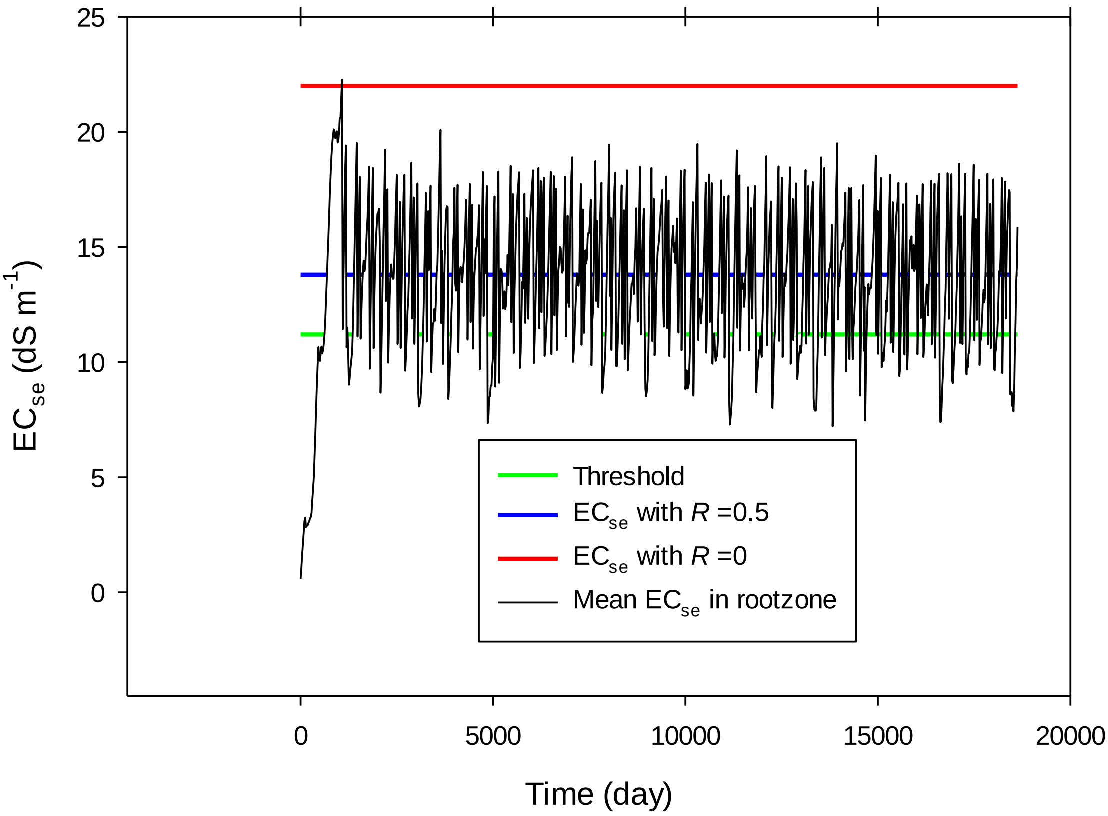

Figure 28 Mean EC_{se} in the rootzone calculated with eqn (8) at Jervois Site compared with the threshold value and estimated EC_{se} values when R = 0.5 (EC_{se} = 13.8 dS m^{-1}) and R = 0 (EC_{se} = 22 dS m^{-1}).

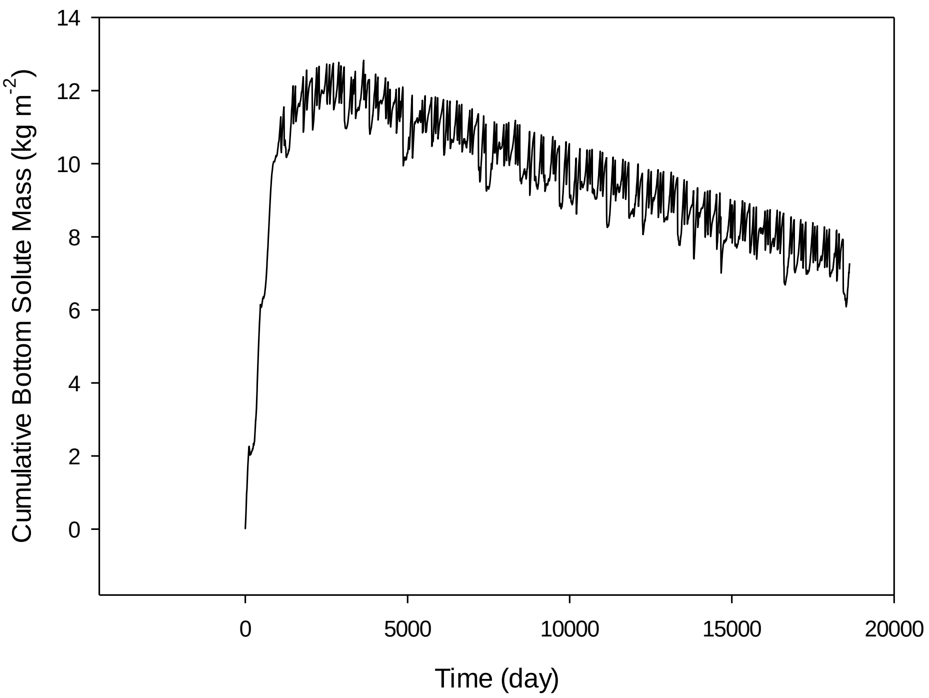

Figure 29 Cumulative salt from water table with time for scenario 7 for the Jervois site.

The ratio of transpiration for scenario 7 is 41,812 mm and scenario 3 is 50,946 mm, which is a ratio of 0.82. This again means that pasture growth could be maintained with larger single irrigations as well as maintenance of the soil condition to avoid salinization but would require a large increase above the present ELMA. The simulations show that with the present ELMA and 100 mm irrigations (scenario 4) a transpiration of ratio with scenario 3 is 0.72. This result suggests that it may be possible to maintain pasture cover with this irrigation but a greater risk would be involved and management of the irrigation would be critical.

4.7 Benefits of ELMA Application to Prevent Soil Cracking and Acidification

Due to the focus on salinity, the current report has not explicitly considered the benefits that applying ELMA could have in preventing soil cracking and acidification as occurred from 2007 to 2010 in the LMRIA. However, such modelling was included as part of the recent South Australian River Murray Sustainability (SARMS) research that was recently completed (Mosley et al. 2016; 2017b). This project used 2 dimensional models and also included the river level interaction. The results of this modelling showed that a minimum number of irrigations (3 per year, 100 mm irrigation depth per irrigation) would have greatly reduced the severity of soil cracking in the 2007 to 2010 extreme drought period. This amount of irrigation (3 ML ha^{-1} $year^{-1}$) is broadly equivalent to the ELMA provided to the southern LMRIA region (Table 1). The modelling also indicated that groundwater level during the same period would be 0.5 to 1 m higher with minimum irrigation. This would have greatly lessened the zone of soil acidification as acid sulfate soils would not have oxidised (i.e. they would have remained saturated in this zone). These results highlight the importance of applying irrigation water, including ELMA, to the LMRIA during drought. The modelling also tested the effect of maintaining the river level, this appeared to have only a minor direct benefit for cracking and soil acidification (Mosley et al. 2017). However a higher river level enables easier irrigation (i.e. either via gravity fed flood irrigation if possible or pumping if this is not possible).

5 SUMMARY

The Scenario 7 HYDRUS modelling results, which are considered most realistic for the boundary conditions and control of saline flux from the groundwater table, show that a moderate level of soil condition and salt tolerant (rye grass) pasture growth could be maintained with irrigation volumes of 5.71 ML/ha in Baseby, and 5.21 ML/ha at Long Flat and Jervois (Table 15). Note the initial 10 year simulation "model warm up" period was excluded from these averages so they represent 41 years of simulation. Soil salinities at each area were similar at the end of the 51 year period simulations using these volumes and ranged between 10−17 dS m^{-1} when converted to a saturated paste extract (EC_{se}). On average these salinities should allow about a 50% yield of rye grass.

The irrigation volumes required in Scenario 7 were 0.73 ML ha^{-1} yr^{-1} lower than the current ELMA at Baseby, 0.75 ML ML ha^{-1} yr^{-1} higher than the current ELMA at Long Flat, and 2.25 ML ha^{-1} yr^{-1} higher than the current EMLA at Jervois (Table 15). However, it is noted that cumulative bottom salt mass was still decreasing at the end of the simulation period with these volumes. Hence lower volumes could be considered. These irrigation volumes are much less than that required to meet the climate deficit and achieve full production (see Scenario 3 in Table 15, approx. 12-13 ML ha^{-1} yr^{-1}) which were comparable to the current maximum irrigation water application rate allowable under the River Murray Water Allocation Plan (WAP, SAMDB NRMB 2016) of 13.92 ML ha^{-1} $year^{-1}$.

Table 15. Comparison of ELMA irrigation volumes (used in Scenarios 4 and 5) with irrigation volumes in Scenarios 3 and 7 (average over 41 years of model simulation, 1970-2010).

Irrigation area	**ELMA (= volumes used in Scenarios 4 & 5)**	**Volume used in Scenario 3**	**Volume used in Scenario 7**	**Volume used in-Scenario 7 minus ELMA**
	ML ha^{-1} yr^{-1}	ML ha^{-1} yr^{-1}	ML ha^{-1} yr^{-1}	ML ha^{-1} yr^{-1}
Baseby	6.44	13.42	5.71	-0.73
Long Flat	4.46	12.38	5.21	0.75
Jervois	2.96	12.48	5.21	2.25

Scenarios 4 and 5 at the current ELMA allocations shows the salt building up to higher levels at the Long Flat (Table 12) and Jervois (Table 14) irrigation areas, relative to Baseby (Table 10). This is driven by the current ELMA distribution with substantially higher (over double) allocations (and water application in the model in these scenarios) at Baseby compared to Jervois. These simulations and the climate data do not support this large variation in water allocation between irrigation areas. Although they show that the ELMA can avoid the excessive salt build up compared to no irrigation at all sites, the simulations show that the transpiration and hence pasture growth would be reduced to around 50% at the Long Flat and Jervois sites. This would pose a greater risk of pasture cover loss in some areas as variation in soil properties and water distribution will mean that variation would also occur in salt distribution.

It must be noted that these simulations were done with the same soil properties, pasture water requirements, ground water concentration and same water table heights. Variation in either soil properties, ryegrass water requirements, water table heights (e.g. during drought) and ground water concentrations could alter the results. Also Scenario 7 involved application of 200 mm of water over a 4 day period, which was required for model stability but is different to most present irrigation practices which would apply this water over a 1−2 day period. Applying a larger volume of water less frequently (as in Scenarios 5 and 7) was more effective in flushing salt than smaller irrigation volumes more frequently (Scenario 4), without too large a penalty on plant growth.

Results using simple leaching fraction calculations gave markedly different results than the more complex HYDRUS simulations. The leaching fraction calculation results showed that little irrigation water was required to manage soil salinity, which is certainly at odds with observed soil salinisation when no irrigation water is applied (Mosley et al. 2017b). HYDRUS simulations are more appropriate in the LMRIA to determine soil salinity dynamics as they can account for salt arising from all water sources (rain, irrigation and groundwater). Although application of volumes equivalent to ELMA will not prevent some increase in salinity in the upper soil profile above typical salinity levels under commercial irrigation, the build up to peak salinities took about 10 years. Where no water was applied (Scenario 2) there was a substantial increase in salt concentrations and mass in the soil profile. Our results indicate volumes equivalent to ELMA are not sufficient for sustaining full pasture production, but will assist in maintaining salt tolerant pasture or other salt tolerant vegetation cover.

6 RECOMMENDATIONS

The analysis presented in this report is fit for purpose for the request made, however there are limitations in several areas as indicated in this report. As a result the following recommendations for further work are made:

1. Measurement of soil physical properties and soil salinities in different regions would be beneficial to better parameterise the model in different regions of the LMRIA.
2. The modelling results here are based on one soil, the water demands and salinity tolerance of one plant species (ryegrass), and a single water table salt concentration and water table height. While these were chosen to represent typical values in the LMRIA, pending the variability in the results from Recommendation (1) it would be prudent to do further simulations with varying of these conditions.
3. Controlled ELMA irrigation trials (at field scale or in mesocosms) and salinity measurements would useful to validate model results.
4. Given that the triggering of the irrigations in the HYDRUS simulations was based on salt concentration at 0.5 m depth, it may be useful to trial the measurement of soil salinity as a trigger for ELMA irrigation in the LMRIA. Currently irrigation in the LMRIA is typically triggered on observations of soil moisture conditions rather than salinity. Salinity may be a more appropriate indicator if salt leaching is the main outcome desired from the ELMA.

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