Comparative Modelling of Water Leakage Under a Lucerne or Annual Pasture. 2. Phase Rotations in Two Environments

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Abstract Phase farming with perennial pastures such as lucerne (*Medicago sativa* L.) is one of the rotations proposed to help reduce groundwater recharge in southern Australia. Using results from part 1 of this series, a spreadsheet model was developed to assess the effectiveness of lucerne in reducing recharge. Phase rotations involving 3 years of pasture followed by three years of crop were modelled for Katanning (annual rainfall 485 mm) and Merredin (annual rainfall 328 mm), assuming excess water from a crop first filled the buffer created by lucerne, and only then became leakage. At Merredin, a buffer of 57 mm (as measured at Katanning) reduced average annual leakage from 20 mm to 6 mm, and at Katanning, leakage was reduced from 82 mm to 55 mm. In order to reduce leakage by 90%, a buffer of approximately 4 times the average annual leakage under annuals (i.e. 80 mm at Merredin and 328 mm at Katanning) was required at both sites. On this basis, lucerne appears to be a more promising land use option for reducing groundwater recharge in drier areas. In Western Australia, the drier parts of the wheatbelt are also the parts most prone to dryland salinity.

Keywords: Drainage; Secondary salinity; Episodic recharge; Spreadsheet model

1. INTRODUCTION

Secondary salinity in southern Australia is largely due to inadequate water use by the annual crops and pastures that have replaced the native perennial vegetation throughout much of the region [McFarlane and Williamson, 2001]. Recent research [Ward and Dunin, 2001] has shown that there is little scope to increase water use by conventional crops and pastures, because water use is constrained entirely by atmospheric conditions throughout winter and early spring. Later in spring and summer, water use is constrained by the rooting depth of the plants, which in turn is often constrained by soil conditions rather than crop species. Perennial pastures such as lucerne have shown promise in increasing water use, because they grow roots deeper into the soil than their annual competitors, and so are in a position to use more water during summer and autumn. The dry soil zone created by this summer activity acts as a buffer against movement of water vertically beyond the root zone (referred to as leakage throughout this paper) during the following winter, when supply (rainfall) is high, but demand (potential ET) is low. Several studies [e.g. Crawford and McFarlane, 1995; Angus et al., 2001; Dunin et al., 2001; McCallum et al., 2001; Ridley et al., 2001]. have indicated that lucerne is capable of creating a dry soil zone (buffer) able to store as much as 150 mm more than a comparable annual crop or pasture. Part 1 of this series [Ward, 2001] showed that the ability of lucerne to reduce water leakage was related simply to the difference in soil water storage at the break of the season, which was 57 mm. By extrapolation, a buffer of 150 mm [Ridley et al., 2001] should reduce total leakage during the cropping phase by up to 150 mm. In the grain-growing regions of southern Australia, average annual groundwater recharge is of the order of 10-50 mm [Nulsen, 1998; Asseng et al., 2001a], and so lucerne appears capable of reducing recharge to this extent.

However, 'average' annual leakage is misleading, in that it can be dominated by single large events, which might only happen one year in ten or twenty, with many years of near-zero leakage in between [Zhang et al., 1999]. In this instance, leakage is referred to as 'episodic'. This occurs particularly for the drier regions of the wheat belt, where leakage may be zero in the majority of years. How this seasonal distribution impacts on the effectiveness of lucerne in reducing water leakage is unknown.

Furthermore, while income from pastures is lower than that from crops, there is no incentive for farmers to grow continuous lucerne. Current farming practice involves a phase of pasture (about 3 years), followed by a phase of cropping (often 3-5 years). Under this scenario, the water leakage from a complete rotation, involving both crop and pasture phases, is the critical measure of lucerne's effectiveness in reducing leakage.

In this paper, a spreadsheet model is used to assess the effectiveness of a 3-year phase of lucerne in a 6-year rotation on long-term average annual recharge at two sites of contrasting average rainfall in the Western Australian wheat belt.

2. METHODS

The SWIM model [Ross, 1990] was used to estimate water leakage from annual vegetation using daily rainfall data (May 1 to December 31) from 1970 to 1995 for Merredin and Katanning in the Western Australian wheat belt. Average annual rainfall for these locations is 483 mm at Katanning and 328 mm at Merredin. The initial soil and vegetation parameters were as described by Ward [2001, part 1 of this series].

A spreadsheet model was then developed to estimate water leakage from a phase rotation involving 3 years of annual vegetation followed by three years of lucerne, using the following assumptions:

- There is no difference between annual crops or annual pastures in terms of water leakage [see Asseng et al., 2001b; Ward and Dunin, 2001].
- Water leakage between January 1 and April 30 was zero. This will not hold in all years, but monthly rainfall totals exceeding 100 mm for any of these months only occurred in 7 out of 108 years of available rainfall records for Katanning, and 4 times in 100 years in Merredin.
- Water leakage under lucerne in its first 8 months (May to December) was equal to water leakage from annual vegetation for the same period. This is supported by trial data from around Australia.
- The buffer created by lucerne was independent of rainfall, and was created fully in the first summer under lucerne pasture. In some field trials (eg Ridley et al, 2001), especially those where buffers larger than about 100 mm were generated, the full buffer required 2 or more summers to develop. This aspect was also modelled here as part of a sensitivity analysis, by setting the buffer to be 75% of the total buffer after the first summer, 90% of the total buffer after the second summer, and 100% of the buffer after the third summer.
- Leakage under the lucerne pasture was zero if leakage under an annual crop in the same year was less than or equal to the buffer size.
- Leakage under the lucerne pasture was reduced by the size of the buffer if leakage under an annual crop in the same year was greater than the buffer size.
- Soils under both lucerne and annual vegetation were at their driest on May 1. In years where significant rainfall (more than about 25 mm per event) occurs in March or April (32 years out of 100 at Merredin) this will not be correct. The impact of this will be to slightly underestimate leakage, particularly for the annual vegetation.
- At the end of the lucerne phase, leakage was equal to zero until cumulative leakage from annual vegetation was equal to the buffer size. In other words, the buffer created by lucerne was completely filled (over several years if necessary) before leakage commenced.

The spreadsheet model was run for all six possible vegetation/year combinations (any specific year could represent either first year lucerne, second year lucerne, third year lucerne, first year annual, second year annual, or third year annual) in each year from 1970 to 1995 (Table 1). Leakage for each buffer size was calculated as the average leakage for all 6 vegetation/year combinations.

In the example provided (Table 1), the buffer was set at 50 mm. In 1974, leakage under continuous annual vegetation would have been 71.6 mm. In the spreadsheet model, rotation combinations where 1974 was second year lucerne, third year lucerne, or first year annual (combinations R2, R3, and R4) had the full buffer available, and so leakage was 71.6-50.0=21.6 mm. In R1, where 1974 was second year annual, the 50 mm buffer had been partially filled by 34.1 mm leakage modelled under annuals in 1973. Leakage under these circumstances was 34.1+71.6–50.0=55.7 mm. In R6, where 1974 was third year annual, a similar argument applies, except that 9.0 mm leakage modelled for 1972 has also gone into the buffer, making leakage for 1974 equal to 9.0+34.1+71.6-50.0=64.7 mm. Similarly, for R5

Table 1. An example of the spreadsheet model run for Merredin rainfall, with the buffer set at 50 mm. Shaded cells represent years where lucerne was grown, and Rn represents the 6 possible different year/vegetation combinations. Note the different behaviour in 1974 depending on the stage of the rotation.

Year	Leakage (mm)						
	Annuals only	R1	R2	R3	R4	R5	R6
1970	4.8	4.8			0.0	0.0	0.0
1971	0.3	0.0	0.3		0.0	0.0	0.0
1972	9.0	0.0	0.0	9.0	0.0	0.0	0.0
1973	34.1	0.0	0.0	0.0	0.0	0.0	0.0
1974	71.6	55.7	21.6	21.6	21.6	65.0	64.7
1975	13.4	13.4	13.4	0.0	0.0	0.0	13.4
1976	0.4	0.4	0.4	0.0	0.0	0.0	0.0
1977	1.0	0.0	1.0	0.0	0.0	0.0	0.0
1978	5.7	0.0	0.0	0.0	0.0	0.0	0.0
1979	9.7	0.0	0.0	0.0	0.0	0.0	0.0

(first year lucerne in 1974), leakage of 0.3 mm in 1971 has also gone into the buffer, and 1974 leakage becomes 0.3+9.0+34.1+71.6-50.0=65.0 mm. The average leakage for Merredin in 1974 under a phase rotation with a buffer of 50 mm was (55.7+21.6+21.6+21.6+65.0+64.7)/6=41.7 mm.

The model was structured to allow the buffer size to be easily modified. Buffer size was varied between 0 and 200 mm at 5 mm intervals, and from 200 mm to 600 mm at 10 mm intervals to assess its impact on leakage in both environments.

3. RESULTS

3.1. Sensitivity of the model to delayed buffer development

Buffer development was delayed in the model by generating 75% of the final buffer after the first summer, 90% of the buffer after the second summer, and allowing the full buffer to be expressed after the third summer (ie going into the first crop after the lucerne phase). There was little impact of delaying the development of the buffer in this way on leakage from the phase rotation (Table 2).

Table 2. Impact of delayed buffer development on average water leakage (mm) from a phase rotation. Kat = Katanning, and Merr = Merredin.

Buffer size	Immediate buffer		Delayed buffer	
	Kat	Merr	Kat	Merr
50	58	7	60	7
100	41	2	43	2
150	29	0	30	0
200	21	0	22	0

3.2. Leakage under annuals

In general, leakage was less at Merredin than at Katanning (Figure 1), as expected from the average rainfall of the two locations. Average leakage from the annual vegetation was 82 mm at Katanning and 20 mm at Merredin. Leakage at Merredin was dominated by a few wet years, shown by the median leakage (8 mm) being substantially less than the average.

Lucerne at Merredin followed the same pattern as lucerne at Katanning, in that the difference in leakage between lucerne and annual vegetation was determined almost entirely by the difference in soil water content at May 1 [Ward, 2001].

3.3. Leakage in a phase rotation

In a phase rotation of three years of lucerne followed by three years of annual vegetation, a buffer of 57 mm (as measured at Katanning) reduced average leakage from 82 mm to 55 mm at Katanning, and from 20 mm to 6 mm at Merredin. A buffer of 150 mm was sufficient to reduce leakage at Merredin to 0 mm, but leakage at Katanning was still 29 mm (Figure 2).

The variation in leakage depending on the timing of the phase rotation was very small (±1 mm) where the buffer was small in relation to average annual leakage, but as the buffer was increased to values greater than the average leakage under annuals, variation became more significant (Figure 2). The highest variation recorded was ±7 mm at Katanning, for a buffer size of 200 mm, and ±4 mm at Merredin, for a buffer size of 70 mm.

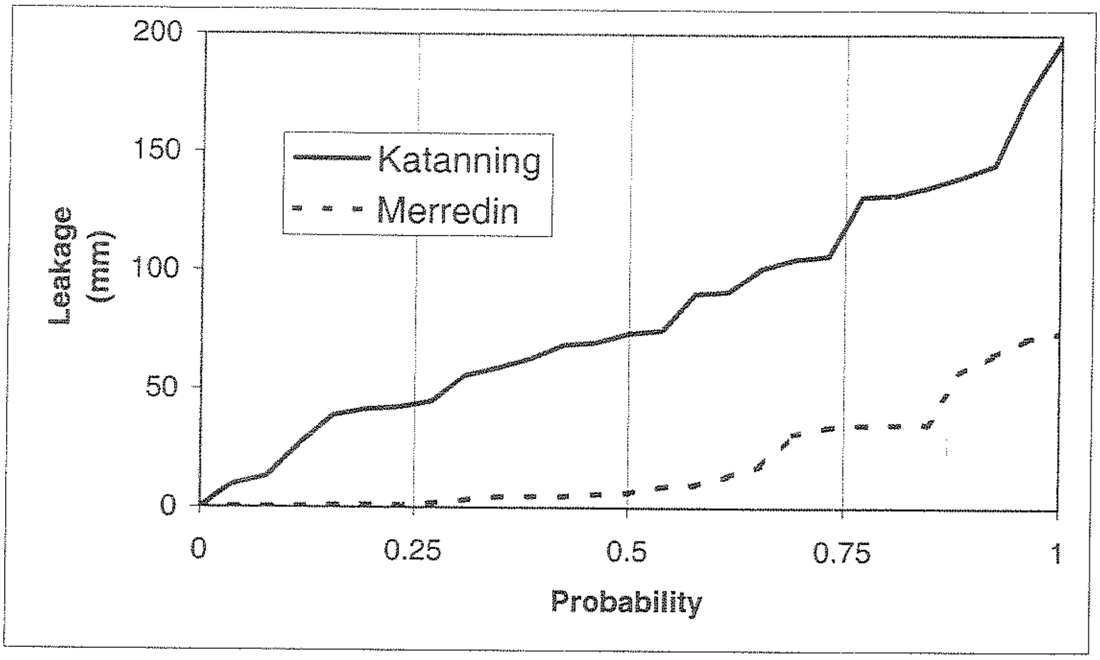

Figure 1. Modelled leakage under annual vegetation for Katanning (average annual rainfall 483 mm) and Merredin (average annual rainfall 328 mm).

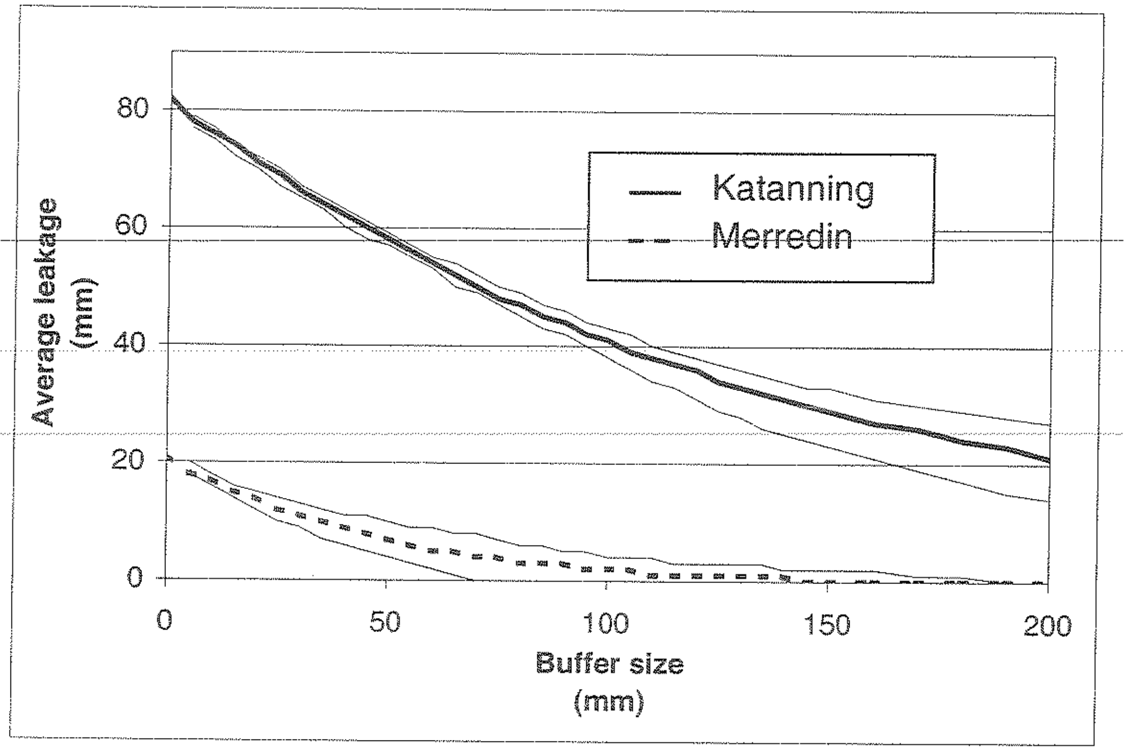

Figure 2. The influence of buffer size on average annual leakage from a phase rotation involving lucerne at Merredin or Katanning. Thin lines represent maximum and minimum leakage from the 6 possible year/rotation combinations.

When reduction in leakage was plotted as a function of buffer size relative to average annual leakage (Figure 3), lucerne was marginally more effective in the area where leakage was less episodic (Katanning). In both locations, a buffer size of approximately 4 times the average annual leakage under annual crops was required to reduce leakage during the whole rotation by 90%. A 50% reduction in leakage was achieved with a buffer of approximately 1.5 times the average annual leakage.

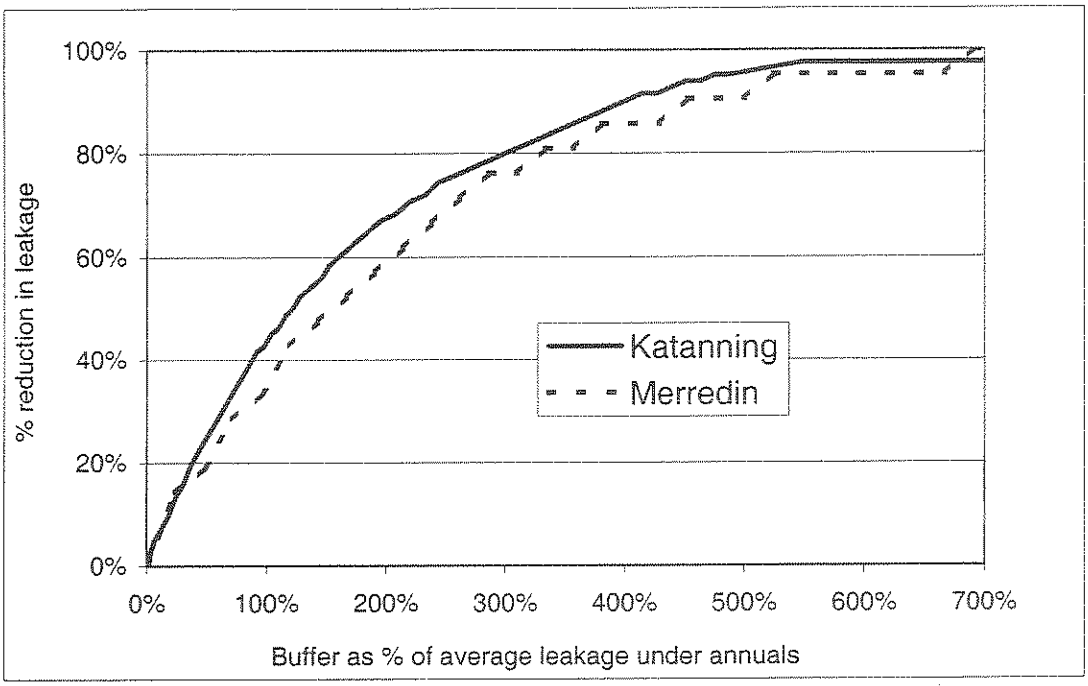

Figure 3. Effectiveness of a phase rotation involving lucerne in reducing average leakage, relative to average annual leakage under crops

4. DISCUSSION

In absolute terms, the incorporation of lucerne, generating a buffer of 57 mm, into a phase rotation reduced leakage by more in the wetter environment (Katanning – an average annual reduction of 27 mm) than in the drier environment (Merredin – a reduction of 14 mm). This is primarily due to the less episodic nature of leakage at Katanning, where substantial leakage occurs in most years.

Recent research has suggested that in order to achieve control of secondary salinity in Western Australia, average groundwater recharge needs to be reduced by about 90% [T.J. Hatton, personal communication]. Modelled data presented here suggests that if lucerne is to be effective, it must generate a buffer approximately four times the size of the average annual water leakage in the absence of perennial vegetation. This relationship held true for two sites of contrasting rainfall and contrasting episodicity of annual leakage. Measured buffers created by lucerne across southern Australia range from about 50 mm up to 200 mm [Latta et al, 2001; Ridley et al., 2001; Ward et al., 2001], indicating that a phase farming system involving lucerne will be most effective in areas where average annual leakage from annual vegetation is less than 50 mm. Maps published by Asseng et al. [2001a] suggest that much of the wheat belt of Western Australia fits into this category. In particular, the lower rainfall areas of the wheatbelt, where the potential for salinity is greatest, stand to benefit the most. However, not all of this land is suitable for lucerne, and the factors that influence the ability of lucerne to create large buffers are still poorly understood. Consequently, further research is necessary to define the areas most suitable for lucerne, and to find alternative perennial species for other areas.

In the model developed here, a strict rotation of three years of lucerne and three years of annual vegetation was imposed. However, while income from crops exceeds that from pasture, farmers will look to maximise the proportion of crop in the rotation. Further research is necessary to develop a decision support tool to allow farmers to switch from crops back to lucerne only when the buffer is full. This will depend on rainfall and leakage from the annual vegetation. For example, at Katanning, the maximum number of years taken to refill a 60 mm buffer was 2, whereas at Merredin, the corresponding figure was 8 years. In other words, farms in the Merredin region could have a rotation of up to 8 years of crops before switching back to lucerne (depending on the run of seasons), whereas farms at Katanning could only expect a maximum of 2 crops between lucerne phases. In both regions, the cropping phase may need to be as short as 1 year if the year of crop corresponds with a year of particularly high leakage.

5. CONCLUSIONS

In absolute terms, lucerne, as part of a phase, is more effective in regions where leakage is less episodic in nature. However, in order to achieve a 90% reduction in leakage, a buffer of the order of 4 times the average annual leakage under annuals needs to be established. Lucerne is more likely to achieve this goal in drier parts of the wheat belt, where average annual leakage is less than 50 mm. These also appear to be the areas in Western Australia where the risk of secondary salinity is highest. Fortunately, the episodic nature of recharge in these areas suggests that the (more profitable) cropping phase can often be extended by several years, making the incorporation of perennials into a phase rotation more financially attractive.

6. ACKNOWLEDGEMENTS

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