IMPROVED LETTUCE ESTABLISHMENT BY SUBSURFACE DRIP IRRIGATION

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STATEMENT OF AUTHENTICATION

The work presented in this thesis, to the best of my knowledge and belief, is original except as acknowledged in the text. I declare that I have not submitted this material, either in whole or in part, for a degree at this or any other institution.

Viola Devasirvatham
# TABLE OF CONTENTS

## LIST OF TABLES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>viii</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
</tbody>
</table>

## ABSTRACT

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>xi</td>
</tr>
</tbody>
</table>

## CHAPTER 1: INTRODUCTION

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

## CHAPTER 2: REVIEW OF LITERATURE

<table>
<thead>
<tr>
<th>1. Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Vegetable production in Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2.1. The NSW and Sydney Basin industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2.2. Irrigation water sources and issues arising</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Water and its measurement and management in irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1. Soil and plant water concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.1. Soil water potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.2. Soil water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.3. The moisture characteristic and concepts of available soil water</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.4. Soil-plant-atmosphere continuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.5. Soil water movement and Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.6. Plant water relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.7. Yield threshold depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.1.8. Soil water balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2. Monitoring soil and plant water in irrigation scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2.1. Tensiometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2.2. Granular matrix sensor/gypsum block</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2.3. Wetting front detector, capacitance probe/frequency domain reflectometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2.3. Time domain reflectometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.2.4. Neutron probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.3. Water balance approaches in irrigation scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.4. Water use efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.5. Irrigation scheduling to improve water use efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
</tr>
</tbody>
</table>

## CHAPTER 3: WATER AND ITS MEASUREMENT AND MANAGEMENT IN IRRIGATION

<table>
<thead>
<tr>
<th>4. Drip irrigation and its adaptation in sub-surface drip irrigation management</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.1. Design and installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.1.1. Lateral drip line</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.1.2. Tape installation depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.1.3. Lateral spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
</tr>
</tbody>
</table>
4.1.4. Installation 27
4.1.5. Emitters 28
4.1.6. Emitter spacing 28
4.2. Flushing capacity 29
4.3. Water application uniformity 29
4.3.1. System uniformity 29
4.3.2. Spatial uniformity in the field 29
4.3.3. Causes and consequences of non-uniformity 30
4.3.4. Minimising non-uniformity 30
4.3.5. Comparison of uniformity in surface and subsurface drip 31
4.4. Management of SDI 31
4.4.1. Discharge rate and irrigation frequency in relation to crop and soil type 31
4.4.2. Fertigation via drip irrigation 34
4.5. Growth and yield of vegetables in surface and sub surface drip irrigation 36
4.6. Problems encountered with SDI 38

5. Soil properties and SDI performance in the vegetable industry 42
5.1. Role of soil texture and structure 42
5.2. Role of soil hydraulic properties 43
5.3. Soil chemical responses to drip and sub-surface drip irrigation 43
5.4. Soil wetting pattern 44

6. Conclusions 45

CHAPTER 3: EFFECTS OF MODIFIED SUB-SURFACE DRIP ON LETTUCE CROP
ESTABLISHMENT, EARLY GROWTH AND SOIL MOISTURE COMPARED WITH
CONVENTIONAL SDI 47

1. Introduction 47
2. General methods 48
2.1. Site location 48
2.2. Soil type 48
2.3. Field preparation 49
2.4. Field layout and general crop culture 49
3. Specific methods 51
3.1. Experiment 1 - Autumn 51
3.2. Experiment 2 – Spring 51
4. Weather data 52
5. Statistical analysis of data 52
6. Results
6.1. Crop establishment 53
6.2. Number of leaves 53
6.3. Leaf size 58
6.4. Lettuce fresh weight 61
6.5. Lettuce dry weight 63
6.6. Volumetric soil water content 64

7. Discussion
7.1. Overall performance 66
7.2. Comparison between the types of SDI 67
7.3. Responses to crop factor and irrigation frequency 69

8. Summary of the results 72

CHAPTER 4: DEVELOPING THE GLASSHOUSE APPARATUS 73
1. Introduction 73
2. Experimental setup 73
   2.1. Selection of silica material 74
   2.2. Hanging water column 75
   2.3. Maintenance of experimental setup 75
3. Theory 75

CHAPTER 5: EFFECT OF MODIFIED SDI AND IRRIGATION FREQUENCY ON SOIL WATER AND COMPONENTS OF THE SOIL WATER BALANCE 78
1. Introduction 78
2. Materials and methods 80
   2.1. Site 80
   2.2. Experimental design 80
   2.3. The experimental apparatus 81
   2.4. Soil types 81
   2.5. Tape types 81
   2.6. Irrigation rate and evaporation (\(E_{\text{pan}}\)) measurements 82
   2.7. Soil water measurements 82
   2.8. Water balance components 83
   2.9. Statistical analysis 84
3. Results 84
   3.1. Pan evaporation in the glasshouse 84
<table>
<thead>
<tr>
<th>Section Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2. Drainage</td>
<td>86</td>
</tr>
<tr>
<td>3.3. Evaporation from bare soil</td>
<td>88</td>
</tr>
<tr>
<td>3.4. Volumetric soil water content</td>
<td>89</td>
</tr>
<tr>
<td>3.5. Soil water potential at 3-5 cm depth</td>
<td>91</td>
</tr>
<tr>
<td>3.6. Soil water potential at 5-10 cm depth</td>
<td>93</td>
</tr>
<tr>
<td>4. Discussion</td>
<td>94</td>
</tr>
<tr>
<td>4.1. Drainage and soil evaporation</td>
<td>95</td>
</tr>
<tr>
<td>4.2. Soil water</td>
<td>96</td>
</tr>
<tr>
<td>5. Summary of the results</td>
<td>98</td>
</tr>
<tr>
<td>CHAPTER 6: GENERAL DISCUSSION AND CONCLUSIONS</td>
<td>99</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>99</td>
</tr>
<tr>
<td>2. Industry context</td>
<td>100</td>
</tr>
<tr>
<td>3. Findings from the research</td>
<td>101</td>
</tr>
<tr>
<td>3.1. Evaluation of modified SDI</td>
<td>101</td>
</tr>
<tr>
<td>3.2. Irrigation management: amount and frequency</td>
<td>104</td>
</tr>
<tr>
<td>4. Future research</td>
<td>107</td>
</tr>
<tr>
<td>4.1. Water saving using modified SDI</td>
<td>107</td>
</tr>
<tr>
<td>4.2. Irrigation management in different soil types</td>
<td>108</td>
</tr>
<tr>
<td>4.3. Nutrient management with SDI</td>
<td>108</td>
</tr>
<tr>
<td>5. Conclusions</td>
<td>108</td>
</tr>
</tbody>
</table>

REFERENCES                                               | 110  |

APPENDICES                                               | 130  |
LIST OF TABLES

Table 1. Soil profile details of the experimental site (after Aiken, 2004) 49
Table 2. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on survival (%) of lettuce (14 DAT) 53
Table 3. Leaf number in lettuce during establishment, for two tape types and three irrigation frequencies in autumn 2007 55
Table 3a. Lettuce leaf appearance rate during crop establishment (leaves per day) for two tape types and three irrigation frequencies in autumn 2007 55
Table 4a. Number of leaves on day 3 (spring 2007) 56
Table 4b. Number of leaves on day 6 (spring 2007) 56
Table 4c. Number of leaves on day 9 (spring 2007) 57
Table 4d. Number of leaves on day 12 (spring 2007) 57
Table 4e. Number of leaves on day 15 (spring 2007) 57
Table 5. Leaf appearance rate (leaves per day) during crop establishment for tape type, irrigation frequency and crop factor (spring 2007) 58
Table 6. The effect of tape type and irrigation frequency (IF) on leaf length (cm) at 7 and 14 days after transplanting (autumn 2007) 59
Table 7. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on leaf length 7 days after transplanting (spring 2007) 59
Table 8. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on leaf length 14 days after transplanting (spring 2007) 60
Table 9. The effects of tape type and irrigation frequency (IF) on fresh weight (g/plant) at 14 DAT (autumn 2007) 62
Table 10. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on fresh weight (g/plant) at 14 DAT (spring 2007) 62
Table 11. The effect of plant position, in relation to the drip line, on lettuce fresh weight (g/plant) at 14 DAT (spring 2007) 63
Table 12. The effect of tape type and irrigation frequency on dry weight (g/plant) at 15 DAT (autumn 2007) 63
Table 13. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on dry weight (g/plant) (spring 2007) 64
Table 14. The effect of plant position, in relation to the drip line, on lettuce dry weight (g/plant) at 15 DAT (spring 2007) 64
Table 15. The effects of tape type and irrigation frequency on volumetric soil water content (v/v) during establishment (autumn 2007) (after irrigation) 65
Table 16. The effect of tape type, irrigation frequency (IF) and crop factor (F) on soil water content (v/v) during establishment (spring 2007) (before irrigation) 65

Table 17. The effect of emitter position on soil water content (v/v) (spring, 2007) (before irrigation) 66

Table 18. Particle sizes of the sand and sandy loam soils 81

Table 19. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 1) at steady state 86

Table 20. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 2) at steady state 87

Table 21. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 3) at steady state 87

Table 22. Water balance components at ‘steady-state’ for the three phases of the glasshouse experiment: pan evaporation ($E_{pan}$), irrigation (I), drainage (D) and soil evaporation (averaged over replicates and soil types) 88

Table 23. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 1) at steady state 90

Table 24. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 2) at steady state 91

Table 25. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 3) at steady state 91

Table 26. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 1) at steady state (3-5 cm depth) 92

Table 27. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 2) at steady state (3-5 cm depth) 92

Table 28. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 3) at steady state (3-5 cm depth) 93

Table 29. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 1) at steady state (5-10 cm depth) 93

Table 30. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 2) at steady state (5-10 cm depth) 94

Table 31. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 3) at steady state (5-10 cm depth) 94
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Field experiment 1 layout</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Field experiment 2 layout</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>Pan evaporation for both seasons</td>
<td>52</td>
</tr>
<tr>
<td>4</td>
<td>Effects of tape type and irrigation frequency on lettuce leaf width during autumn 2007</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Effects of tape type and irrigation frequency on lettuce leaf width during spring 2007</td>
<td>61</td>
</tr>
<tr>
<td>6</td>
<td>Plant fresh weight response to irrigation frequency in modified SDI (left) and conventional SDI (right)</td>
<td>70</td>
</tr>
<tr>
<td>7a</td>
<td>Pan evaporation in Phase 1</td>
<td>84</td>
</tr>
<tr>
<td>7b</td>
<td>Pan evaporation in Phase 2</td>
<td>85</td>
</tr>
<tr>
<td>7c</td>
<td>Pan evaporation in Phase 3</td>
<td>85</td>
</tr>
<tr>
<td>8</td>
<td>Effects of tape types and irrigation frequencies on mean soil evaporation (mm) from bare soil at steady state</td>
<td>89</td>
</tr>
<tr>
<td>9</td>
<td>Plant fresh weight response to volumetric soil water content in both seasons</td>
<td>102</td>
</tr>
<tr>
<td>10</td>
<td>Plant fresh weight response to variation in volumetric soil water within the bed during spring 2007</td>
<td>103</td>
</tr>
</tbody>
</table>
ABSTRACT

Vegetables are grown in the peri-urban zone throughout Australia in diverse soil types and climates. Irrigation allows cropping throughout the year. Competition for water and adverse environmental impacts from irrigation will increasingly influence access to water and the price paid. These forces are particularly strong in the Sydney Region, where improved irrigation techniques are urgently needed.

A review of literature showed that sub-surface drip irrigation (SDI) has the potential to achieve high water use efficiency and crop yields, as well as reduce drainage and runoff and the associated environmental risks. However, disadvantages of SDI include ‘tunnelling’, poor soil surface wetting, and risky crop establishment. The research reported in this thesis, evaluated ways to overcome these problems, including a new product (KISSSTM) that has a narrow band of impermeable material below the drip tape, and geotextile above. It was hypothesised that the impermeable layer would create a temporary watertable, from which the upward flux of water would be greater than in conventional SDI and the drainage less. The research questions were:

1. Does an impermeable layer beneath the drip tape (modified SDI) improve surface soil water conditions and crop establishment, compared with conventional SDI?

2. Does the modified SDI (M.SDI) offer any advantage over using conventional SDI (C.SDI) with increasing irrigation amount or frequency?

A further objective was to determine how irrigation management with the modified SDI should take account of soil type and evaporative demand.
Field experiments at Richmond, NSW compared C.SDI and M.SDI on a sandy soil in autumn (mean pan evaporation 2 mm/day) and spring (mean evaporation 6 mm/day) to investigate lettuce crop establishment. The treatments were two drip tape types (M.SDI, C.SDI) and three irrigation frequencies (1, 2 and 4 times per day). Irrigation application volume was calculated by using a crop factor of 0.4 in autumn. In spring, crop factors of 0.4 and 0.8 were compared.

Modified SDI improved crop establishment compared with conventional SDI. The difference in seedling survival was numerically small but significant (p<0.05), indicating a superior environment for establishment in the M.SDI. This was reflected in higher leaf appearance rates in the spring experiment. In both experiments, leaves were longer and wider with the M.SDI, and plant fresh weights were greater at the end of the crop establishment period. The differences in fresh weight were substantial, with the M.SDI system recording average increases over the C.SDI of 16% and 25% in the autumn and spring experiments, respectively. Plants were also more uniform with the M.SDI.

In both experiments, plant weight was closely related to volumetric soil water content, regardless of the source of variation in water content: tape type, crop factor, irrigation frequency, or location within the plot.

Soil water and plant weight responded to increased irrigation frequency (IF) and crop factor (CF, included in spring only) with both tape types. The effects of CF and IF were additive within tape types. So, whilst the negative effect of reduced irrigation amount can be offset by increased irrigation frequency, the best growth was obtained where both were high. However, for every combination of CF and IF, plant growth with the modified SDI exceeded the conventional SDI. With the combination of high irrigation frequency (4/day) and a high crop factor (0.8), the modified SDI resulted in a 35% increase in plant
fresh weight over conventional SDI. Importantly, at high irrigation frequency (4/day) but with only half the amount of irrigation (CF 0.4 versus 0.8), plant weight with modified SDI was similar to conventional SDI (actually 10% greater). Soil water content was also more uniform in the M.SDI treatment.

A glasshouse experiment quantified the components of the water balance under irrigation with conventional and modified sub-surface drip irrigation, in sand and sandy loam soils under different evaporation demand. A tension table in the base of each large pot (50x35x5 cm) was used to maintain a suction of -60 cm at the base. Each treatment was subjected to a sequence of different irrigation frequencies, one per two days; and one, two and four per day. Data for drainage and soil water were recorded daily, and averaged over the last three days when daily drainage approached steady-state for any irrigation frequency.

The M.SDI system generally resulted in lower drainage than with the C.SDI, regardless of soil type, irrigation frequency, evaporative demand, and irrigation rate. As the amount of daily irrigation (I) was known and equal for all treatments, soil evaporation (E_{soil}) was estimated from drainage (D) using the simplified soil water balance equation: 

\[ E_{soil} = I - D \] 

Thus soil evaporation was the inverse of drainage. The upward flux of water to meet the evaporative demand was greater in the M.SDI, and it was greater with more frequent irrigation. Soil water content and potential were both higher with the M.SDI. They were also higher with frequent irrigation, as in the field experiment. Overall, the M.SDI had less drainage than conventional SDI, greater upward flux of water (soil evaporation), and wetter surface soils. The findings are consistent with the hypothesis that an impermeable layer beneath the drip tape creates a temporary watertable, increasing the upward flux of water.
Both the field and glasshouse experiments showed the benefit of dividing the daily irrigation requirement into smaller, more frequent pulses, for both types of drip tape, regardless of the soil types and climates investigated. Whilst increased irrigation amount and irrigation frequency both increased soil water content and plant growth, the best performance was when both irrigation amount and frequency were high. Frequent irrigation (4/day) was essential to obtain the improved crop growth with the M.SDI and a high crop factor in the spring experiment.

These positive responses to tape type and irrigation frequency were obtained at relatively low and high evaporative demand (2, 6 mm/day), and in soils with different texture (coarse sand, sandy loam). So the modified drip tape and more frequent irrigation appear to be reliable, broad recommendations. No specific recommendation can be made on the present data regarding irrigation frequency in relation to evaporative demand, although it might be expected that under very high demand more frequent irrigation will be required unless the modified drip tape can be made to hold a greater volume of water against drainage.

In relation to the first objectives of the study, it is concluded that the modified SDI (KISSSTM) improves surface soil water content and uniformity, and has the potential to overcome the plant establishment problems associated with conventional SDI. It does so whilst saving water and reducing environmental risk (drainage and/or runoff). With respect to research question 2, irrigating with more water, or more frequently, did improve seedling growth, but the modified drip tape (KISSSTM) retained an advantage in terms of both establishment and growth at any combination of irrigation amount and frequency. Further research is required to develop guidelines for using the M.SDI in specific soils and climates, especially for heavier-textured soils and more extreme evaporation.
CHAPTER 1: INTRODUCTION

Efficient use of water is a key factor for irrigation management globally, with widespread efforts being made to increase water productivity and reduce the environmental impacts of irrigation. With future water scarcity and climate change, management of water will become an increasingly important issue in intensive vegetable production.

With peri-urban irrigated agriculture such as in the Sydney region, NSW, Australia, competition for water resources is acute, and the need for improved irrigation management is most important (NSW Agriculture, 2002). Intensive vegetable production is an important and expanding industry in peri-urban Sydney (Johnson et al., 1998). Many vegetable growers in this area use potable water as the major water source (Dang, 2004). Competition for water with urban users has led to uncertainty about the security of future water supplies.

The Sydney region enjoys a sub-humid climate with an average rainfall of 800-1000 mm spread over most months (Bureau of Meteorology, 2007). The rainfall and mild temperatures enable vegetables to be grown year-round, but access to irrigation is required in most months to provide water security (Hollinger, 1998). Soils vary greatly, but the three dominant soil types used for vegetable production in Western Sydney are the alluvial soils along the Hawkesbury-Nepean river system and the texture-contrast soils based on Hawkesbury sandstone, both of which have sandy surface soils, and the soils derived from Wianamatta shale which have clay-loam surface soils (Rogers, 1988).

The Sydney region is ideal for lettuce (Lactuca sativa), which is grown year-round (McDougall, 2002) by direct seeding or, more commonly, by using nursery-raised ‘transplants’ (Tony, 2004). Lettuce is irrigated mostly by overhead sprinklers (Sutton and Merit, 1993). Drip irrigation is not widely used for lettuce in NSW, apparently because of
higher costs (low durability), interference with normal cultural practices necessitating removal between crops, and the lack of local guidelines to adapt system design and management to the diverse soils and annually varying climate (Hollinger et al., 2001; Cornish et al., 2005). In other respects, drip irrigation should be suitable (Tony, 2004). The irrigation water requirement of drip irrigated plants can be less than half that of sprinkler irrigated plants (Sutton and Merit, 1993).

Subsurface drip irrigation (SDI) is an alternative to conventional drip irrigation, which could become an attractive option to lettuce growers in the Sydney region as the cost over the life of the product can be less than with surface tape, and because reduced tillage using semi-permanent beds (Senn and Cornish, 2000) has removed the need for deep cultivation between every crop.

The advantages of SDI compared to surface drip irrigation include direct application of water to the root zone, less evaporation from soil, potentially greater water use efficiency and fewer weed and disease problems (Phene et al., 1987). SDI has been found to increase yield over surface drip (Sakellariou-Makrantonaki et al., 2002); furrow irrigation (Hanson et al., 1997); and sprinkler irrigation (DeTar et al., 1996), providing the SDI system receives good irrigation scheduling (Haman and Smajstrla, 2002).

SDI also has several important potential disadvantages, including ‘tunnelling’, variable soil surface water and risky establishment (Mizyed and Kruse, 1989; Lamont et al., 2002; Lamm and Camp, 2007). Amongst these problems, poor germination and/or crop establishment remains the major challenge with SDI (Raine and Foley, 2001). Crop establishment is often poor (Lamm, 2002) due to insufficient surface soil moisture to meet the demands of seedlings or seeds (Zimmer et al., 1988).
One approach to improving establishment with SDI has been to modify the buried drip tape by adding an impermeable plastic barrier below the tape, as in the Capillary Root Zone Irrigation system (CRZI). CRZI reduced variability in soil surface wetting but did not improve establishment (Charlesworth and Muirhead 2003; Deery, 2003), mainly due to the hydraulic properties of the particular soils, which resulted in adequate establishment in all treatments. CRZI has undergone extensive development, in particular the width of the impermeable layer (now 100 mm), and it is now sold under the trade name KISSS™ (hereafter called “modified SDI”). It has not been thoroughly evaluated. In addition to modifying tape design, surface soil water can be improved by shallow tape installation and increased irrigation frequency (Burt and Styles, 1994), although these approaches have met with limited success, leading Harris (2005a, b) to conclude that possibly crops cannot be established this way at all, without an additional source of water.

The broad aim of this project was to facilitate the adoption of SDI by improving surface soil water conditions and crop establishment. Lettuce was used because of its importance in the Sydney region, and ‘transplants’ were used, according to local practice.

The research questions were:

1. Does an impermeable layer beneath the drip tape (modified SDI) improve surface soil water conditions and crop establishment, compared with conventional SDI?

2. Does the modified SDI offer any advantage over using conventional SDI with greater irrigation amount or frequency?

A further objective was to determine if irrigation management with SDI should take account of soil type and evaporative demand.
The work was underpinned by the hypothesis that the strip of impermeable material below the buried drip tape created a temporary watertable at each irrigation, from which the upward flux of water to the soil surface was increased.
CHAPTER 2: REVIEW OF LITERATURE

1. Introduction

Irrigation in the Australian vegetable industry has traditionally been dominated by the use of surface irrigation. However, increasing pressures on water availability, the potential yield increase through improved control of soil and plant water relationships, and the benefits of reduced labour, fertilizer and pesticide cost, have raised vegetable grower interest in alternative irrigation application techniques, including drip irrigation systems.

Drip irrigation has the potential to use scarce water resources most efficiently to produce vegetables (Locascio, 2005). The modern development of drip irrigation started in Great Britain during World War II and continued in Israel and other countries (Camp, 1998). The major benefits of drip irrigation are the ability to apply low volumes of water to plant roots, reduce evaporation losses, and improve irrigation uniformity (Schwankl, et al., 1996).

Subsurface drip irrigation (SDI) applies water below the soil surface, using buried drip tapes (ASAE, 2001). It has many benefits over conventional drip irrigation (Singh and Rajput, 2007). The biophysical advantages are the lower canopy humidity and fewer diseases and weeds (Camp and Lamm, 2003). The yield and quality of vegetable crops can improve with a buried drip system compared with a surface drip system (Sammis, 1980; Phene et al., 1987; Bar-Yosef, 1989). Environmental benefits include the ability to manage nutrient and pesticide leaching and the threat to groundwater (eg Lamm, 2002). However, SDI is not without problems (Lamm, 2002; Harris, 2005b; Lamm and Camp, 2007).

This review provides context for the research described in this thesis by first considering the vegetable production industry in Australia, with a particular focus on issues
for production in the Sydney region (Section 2). Basic concepts of water and its management in irrigation are considered in Section 3. Drip irrigation design and management and its adaptation to SDI are reviewed in Section 4, including identification of problems with SDI. These are related to soil factors in Section 5, leading then to Conclusions relevant to the research reported here.

2. Vegetable production in Australia

Vegetable production in Australia is dominated by Queensland, New South Wales and Victoria, where more than 4,000 farms produce vegetables for sale (ABS, 2005). The largest area is in Queensland. Over the four years (2000-2004), the number of farms fell by 19 %, but the industry continued to be dominated by small farms. The value of output from the typical vegetable farm rose from $281,000 in 2000-2001 to $387,000 in 2003-2004. Fifty years ago, the average Australian consumed around 130 kg of vegetables annually. Today, per capita consumption is 162 kg. If vegetable consumption increases at the same rate, the per capita consumption should reach around 188 kg by 2050 (AUSVEG, 2004). Consumer demand for vegetables is rising over the long-range, so there is need for continued expansion in vegetable production.

Most vegetable farming is characterised by intensive management including irrigation. A major problem faced by farmers is the cost of and access to water (Hickey et al., 2006). However, improvements in the productivity of irrigation water are being made. For example, the average return from vegetable production per ML rose from $1,762/ML in 1996/97 to $3,207/ML in 2000/01 (ABS, 2002). An industry report attributes this to increased use of water-efficient delivery systems such as drip irrigation, irrigation
scheduling and soil moisture monitoring, which help achieve a good quality product resulting in higher prices in the market (Hickey, 2005).

2.1. The NSW and Sydney Basin industry

New South Wales’s vegetable production districts are the Sunraysia, Riverina – MIA (Murray Irrigation Area), Slopes and Tablelands and Sydney Basin (McMullen, 2000). The Sydney Basin including Greater Western Sydney, the focus of this thesis, supplies the full range of fresh vegetables to the local market. The vegetable industry in NSW contributes approximately $300 million to the economy. Nearly 26 % of the total value of this industry is produced by the Sydney Basin, where the major vegetable crops are lettuce (*Lactuca sativa* L.), cabbage (*Brassica oleracea* var. Capitata), and cauliflower (*Brassica oleracea* var. Botrytis) (Hickey and Hoogers, 2006). Most ‘Asian vegetables’ in NSW are produced on 340 small farms of about 5-20 acres in Western Sydney, equally contributed by Chinese, Cambodian and Vietnamese growers (Nguyen, 2000).

Lettuce is a common salad vegetable in Australia. Several types of lettuce are available: crisphead, butterhead, romaine (cos) and leaf varieties (Tony, 2004). Lettuce has a short growing season, commonly reaching maturity in about 6 to 10 weeks from sowing, depending upon the type. All commercial lettuce production is uses ‘transplants’ or nursery-raised seedlings. They require less time in the field (Kinsela, 1985; Wallace, 2000) allowing more intensive cropping. They also overcome establishment problems and the cost of thinning (Tony, 2004).

FAO (2000) defined the area of farm units surrounding towns as ‘peri-urban’, supplying fresh vegetables, fruit. In all countries, rural to urban migration is placing pressure on the peri-urban area where housing and industrial development interact with food production (Brook and Davila, 2000). Sydney’s peri-urban zone is characterised by an
inner zone of market gardens, an intermediate zone of poultry-horticulture and an outer
zone of dairy or mixed farming (Johnson et al., 1998).

According to the Agricultural Land Classification System, the Western Sydney
Peri-Urban Horticultural region is arable land Class1 (Hulme et al., 2002) with high to very
high productivity.

2.2. Irrigation water sources and issues arising

Many peri-urban vegetable growers in the Sydney region use potable water from
the Sydney water supply as their main water source (Dang, 2004), although there is also a
significant industry based on irrigation from the Hawkesbury-Nepean River and its major
tributary (South Creek) as well as farm dams. Out of 3,000 irrigators, approximately 1,500
are river pumpers, 750 draw from farm dams and the remaining 750 irrigators, mainly
vegetable growers, use town water (Hickey et al., 2006).

Charges for town water used by vegetable growers are based on the commercial
Tier 1 rate of $1.20/kilolitre from October 2005. Peri-urban vegetable growers pay
annually ~A$10,000 to A$20,000 for water (Hickey et al., 2006). They are also affected by
water restrictions during periods when water levels in the Sydney Water Reservoirs are low
(Sydney Water, 2007), and will compete increasingly with urban and industrial users
(Maheshwari and Simmons, 2003).

Farmers in this area practise intensive horticulture. Irrigation is excessive and not
uniform, because overhead sprinklers are most common, and mostly farmers do not use any
form of irrigation scheduling or soil water monitoring (Senn, 2001; Maheshwari et al.,
2003). Drip irrigation is rarely used in the Sydney region, apparently because surface drip
systems are seen as costly, they are said to interfere with normal cultural practices, and
there are no guidelines for designing and managing drip systems across the diverse soils
and climates of the Sydney region (Cornish et al., 2005). Excessive irrigation on the farms investigated by Cornish and Hollinger (2002) was associated with high stormwater runoff and nutrient loss from farms, although the magnitude of loss depended on soil type (Hollinger et al., 2001). In two on-farm trials, Hollinger et al. (2001) found that SDI greatly reduced irrigation requirement. It also reduced stormwater runoff because the soil profile was generally drier and accepted more rainfall before runoff occurred.

Subsurface drip irrigation could overcome two main objections to surface drip irrigation. One is the high cost associated with frequent removal and replacement, provided the SDI system lasts long enough to offset the high initial set-up cost. The other is interference with cultural practices. Reduced tillage based on semi-permanent beds (Senn and Cornish, 2000) requires only shallow cultivation, potentially allowing SDI tube to remain undisturbed for many years, without impeding cultural practices.

These findings demonstrate the significant need in the Sydney region to improve irrigation efficiency and help address the pressures of increasing cost of water and restrictions on supply. Given the irrigation systems and management practices currently being used, there is scope to meet this need with drip or particularly subsurface drip irrigation, although installation and management will need to be adapted to the range of soils and the seasonally varying climate of the region.
3. Water and its measurement and management in irrigation

3.1. Soil and plant water concepts

3.1.1. Soil water potential

Soil water potential is expressed in energy terms (bars or MPa). The difference in energy between pure water and that of soil water at standard pressure and temperature is called the soil water potential. The total water potential can be expressed:

\[ \psi_t = \psi_g + \psi_m + \psi_p + \psi_o \]

where, \( \psi_t \) = the total soil water potential energy, \( \psi_g \) = the gravitational potential energy, \( \psi_m \) = the matric potential due to capillary pressure, \( \psi_p \) = the pressure potential, \( \psi_o \) = the osmotic potential due to salts (Don Scott, 2000). To determine the potential energy status of soil water, piezometers, tensiometers and psychrometers are commonly used (Goldhamer and Snyder, 1989) (Section 3.2.).

3.1.2. Soil water content

Soil water content is expressed as the mass of water in unit mass of soil (gravimetric) or as volume of water in unit volume of soil (volumetric) (Jalota et al., 1998). Gravimetric water content (\( \theta_g \)) is measured by weighing the soil when wet (\( m_{\text{wet}} \)) and again after drying at 105°C (\( m_{\text{dry}} \)).

\[ \theta_g = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} \]

Volumetric water content (\( \theta_v \)) is the volume of liquid water per volume of soil, and can be calculated from \( \theta_g \) using bulk density (\( \rho \)):

\[ \theta_v = \frac{\text{volume}_{\text{water}}}{\text{volume}_{\text{soil}}} = \frac{m_{\text{water}}}{\rho_{\text{water}}} / \frac{m_{\text{soil}}}{\rho_{\text{soil}}} = \theta_g * \frac{\rho_{\text{soil}}}{\rho_{\text{water}}} \text{ (where } \rho_{\text{water}} \text{ is usually assumed } = 1.0 \text{ g/cm}^3). \]
Relationships between water content and potential are important for understanding water flow in soil (Noborio et al., 1999) (Section 3.1.4).

3.1.3. The moisture characteristic and concepts of available soil water

The energy of soil water and soil water content are related by the moisture characteristic (Prunty and Casey, 2002). In saturated soil, all pores are filled with water and the water potential is zero. As suction is increased, progressively smaller pores drain so the soil water content decreases and the water potential becomes more negative. At very high suctions, only the very small pores retain water. In light to medium textured soils (sands, sandy loams, loams and clay loams), soil structure can evidently affect the soil moisture characteristic, while in heavy textured soils the influence of structure is less distinct (Williams et al., 1983).

Field capacity is defined as the water content of the soil following drainage of a saturated soil profile underlain by dry soil for about 24 – 48 hours depending on soil types (Hardy, 2004). The soil water potential at field capacity is variously defined as around -0.1 bar to -0.3 bar (-0.01 to -0.03 MPa) depending on soil texture and whether the soils have been homogenised or they are structured (as in the field condition) (NEH, 1991). The permanent wilting point is the soil water content at which plants are unable to absorb soil water, and wilt permanently (Ley et al., 2006). The soil water potential at this point is usually considered to be -15 bars (Sankara and Yellamanda, 1995), although the actual value will depend on plant type and the demand for water. The available water in a soil is the amount of water that can be utilized by plants for their growth and development. It is

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1 Field scientists often measure the upper drained limit for field capacity, and the lower limit of extraction for wilting point, reflecting the lack of precision in the field capacity and wilting point concepts.
commonly taken to be the difference between the water contents at field capacity and the permanent wilting point.

3.1.4. Soil-plant-atmosphere continuum

Soil-plant-atmosphere relationship recognises that all components of the field environment (the soil, the plant, the atmosphere), when taken collectively, form a physically integrated and dynamic system. The water movement inside the system is known as soil-plant-atmosphere continuum (SPAC) (Hillel, 2004). Whilst water generally moves from soil to the plant and then into the atmosphere, when the soil is dry and the atmosphere is near saturation, water may move in small quantities from plants into soil (Sankara and Yellamanda, 1995). The flow path of water through SPAC is complex with a series of resistances offered by the different components of the system\(^2\). According to Don Scott, (2000) plants offer little resistance when the soil has sufficient moisture and the atmospheric conditions are moderate. When soil dries, water deficits develop in plants and stomata close partially or completely. Under this condition, plants offer greater resistance to water movement (Barrs and Weatherley, 1962).

3.1.5. Soil water movement and Hydraulic conductivity

The sum of the suction and gravitational potentials is defined as the hydraulic head (Hillel, 1972). The hydraulic head determines the direction and rate of water movement. Water moves from soil with lower to higher potential.

In this research work, we are concerned about upward flux of water, soil matric potential and evaporative demand. The scientific principle underpinning evaluation of the modified SDI in this research is that the water required for crop establishment is met by upward flux from the subsurface drip.

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\(^2\) Plant physiology research has established that ‘plant signals’ also regulate flow through the plant, but this is beyond the scope of this thesis.
Hydraulic conductivity is a measurement of the ability of the soil to conduct water and depends upon the permeability of the soil to water (Don Scott, 2000). Knowledge of the hydraulic conductivity of soil is important to the understanding of soil-water behaviour including the movement of water and solutes within the soil profile and studies of water uptake by plant roots.

Hydraulic conductivity depends greatly on soil water content (Miyazaki, 2006), so it is often determined in both the saturated and unsaturated condition (Lal and Shukla, 2004). Saturated hydraulic conductivity pertains to the conductivity of soil when all pores are filled with water, whereas conductivity is unsaturated when pores are partially filled. The soil factors affecting hydraulic conductivity include the pore geometry, soil structure and presence of entrapped air in the soil pores (Jalota et al., 1998).

3.1.6. Plant water relations

Total plant water potential ($\psi$) includes three components (ignoring gravitational):

$$\psi = P + \pi + \tau$$

where, $\psi =$ water potential in the plant, $P =$ pressure or turgor, $\pi =$ osmotic potential, $\tau =$ soil matric potential (Turner, 1981).

Stomatal closure starts if plant water stress occurs, following decreasing soil water potential, indicated by a fall in $\psi$ below a threshold value. The decrease of 0.5-1.0 MPa in soil water potential normally takes place over days and weeks the plant may be able to adjust. As the soil continues to dry, a plant can be considered under water stress although there may be little change in the midday water potential of exposed leaves (Wenkert, 1983). The $\psi$ at which the stomata close will depend on the osmotic potential in the leaves and rate of drying.
Plants suffering from water deficits have a reduced leaf area and reduced root and shoot development (Jordan, 1983). Leaf area or leaf area index (LAI) is an important growth parameter for irrigation management (Human and Grobler, 1990). During early crop growth, LAI is low and influenced by row spacing. Although transpiration is low at this stage, significant evaporation can take place when the topsoil is wet. In dry soil, evaporation decreases (Ritchie, 1983).

3.1.7. Yield threshold depletion

Yield threshold depletion (YTD) is the amount of water that can be depleted from the soil before there is an effect on yield or quality of crop. If the YTD is known, the soil water balance can also show the maximum time allowable between irrigation. Commonly, a crop should be irrigated before reaching the YTD level. YTD depends upon soil, plant and climatic factors. Crops differ in their sensitivity to water stress. Yield threshold depletions are often less for vegetable crops than field crops (Grattan et al., 1988), presumably because shallow rooted plants exploit less soil and therefore are less well buffered against changes in soil water.

3.1.8. Soil water balance

The soil water balance can be variously expressed. For irrigation research:

\[ \text{ASW}_1 - \text{ASW}_2 = P + I - (ET + R_o + D), \]

ASW is available soil water at times 1 and 2, \((\text{ASW}_1 - \text{ASW}_2)\) is the change in soil water during the interval \(t_1\) to \(t_2\), and \(P\) = precipitation, \(I\) = irrigation, \(ET\) = evapotranspiration, \(R_o\) = surface runoff and \(D\) = deep percolation beyond the root zone, all for the interval \(t_1\) to \(t_2\) (Sankara and Yellamanda, 1995). If \(\text{ASW}_1\) is the desired state and \(\text{ASW}_2\) is the present state, then irrigation required to return the soil water to the desired state (the replenishment
of water use in the period), \((\text{ASW}_1 - \text{ASW}_2)\) can be estimated by assuming \(R_o\) and \(D\) are zero\(^3\): Irrigation requirement = \(\text{ET} - (\text{I} + \text{P})\)

In budgeting approaches to irrigation scheduling, \(\text{ET}\) is estimated from potential evaporation combined with the use of a crop coefficient (Hartz, 1999).

Sankara and Yellamanda (1995) suggested a simplified water balance equation, used by Burt (1999) to calculate the components of the water balance when water was applied to a bare soil surface:

\[ \text{E} = \text{I} - \text{D}, \]

where \(\text{E}\) = Evaporation, \(\text{I}\) = Irrigation and \(\text{D}\) = Drainage. This equation is used to calculate \(\text{E}\) later in this thesis.

### 3.2. Monitoring soil and plant water in irrigation scheduling

Successfully operating and managing an irrigation system requires a proactive monitoring approach to managing soil water. There are three different approaches to monitoring and irrigation scheduling, derived from Goldhamer and Snyder (1989).

i. Soil-based methods estimate soil water status by its appearance, feel or, more objectively, by water content or suction. The main objective methods are described below.

ii. Plant-based methods include visible symptoms such as wilting, that reflect leaf turgor and thus indirectly leaf water potential, the Scholander or ‘pressure bomb’ that measures plant water potential, and non contact thermometry with an infrared thermometer (a water stressed plant transpires less and is cooled less by evaporation).

iii. The water budget approach, which estimates crop water use from weather data and, from this, the irrigation requirement. This is described in Section 3.3.

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\(^3\) Both \(R_o\) and \(D\) are difficult to measure on-farm and are commonly ignored in practice. Irrigation above the irrigation requirement is presumed drainage (Post et al., 1985). The same applies to rainfall after irrigation.
Measurements of soil water can be used to indicate when to irrigate, thus avoiding over and under irrigation. Soil water sensors measure either soil water potential (SWP) or volumetric soil water content (VSWC). Devices for measuring potential include the tensiometer, gypsum blocks and granular matrix sensor (Shock et al., 2005). A variety of FDR (frequency domain reflectometry) (Stirzaker et al., 2005), TDR (time domain reflectometer) (Charlesworth, 2005) and capacitance probes (Fares and Alva, 2000) are available for measuring volumetric soil water content.

3.2.1. Tensiometer

Tensiometers measure only soil water potential. They do not provide direct information on the amount of water held in the soil (Whalley et al., 1994). The use of tensiometers for irrigation scheduling has been widely reported for over thirty years (Pogue and Pooley, 1985; Goyal and Rivera, 1985; Hartz, 2000), although they remain infrequently used in practice in peri urban area of Australia (Maheshwari et al., 2003).

There has been much research on the appropriate depth of placement and water potential guidelines. Recommendations vary with soil type and crop. As an example, the tensiometer should be placed about 15 cm deep in the soil for shallow rooted crops (e.g. lettuce, Owens et al., 2003) and at 30 cm for deep-rooted crops (e.g. tomatoes, melons, Hoffmann, 2007).

The main limitation with tensiometers is they operate only in water potential up to -75 kPa. Further drying leads to breaks in the water column and a high degree of maintenance (Giddings, 2000). Also farmers will often want to deplete soil water beyond the range of the tensiometer, meaning that some interpretation needs to be made, for example from soil water tension deeper than the zone of greatest root proliferation.
3.2.2. Granular matrix sensor/gypsum block

The granular matrix sensor is similar to the gypsum block, although apparently more durable. It operates on the principle that resistivity of the block depends on its moisture content, which in turn depends on soil water potential. Like the gypsum block, the granular matrix sensor has been reported to have slow response times in some circumstances and each sensor needs calibration (Shock et al., 1998). However, both sensors are inexpensive. Granular matrix sensors operate in the range 0-0.2 MPa, and therefore have a wider range of applications than the tensiometer. In a comparison of instruments, Munoz-Capena et al. (2005) found that granular matrix sensors (and tensiometers) were the most suitable for automatic drip irrigation. There appear to have been advances in design and performance over time, and Shock et al. (2004) concluded that it was a very effective irrigation scheduling aid for drip irrigated mint and onions on silt loam soils.

3.2.3. Wetting front detector, capacitance probe/frequency domain reflectometer

The wetting front detector, which originated from Australia, is a soil moisture-monitoring device which can be used to detect wetting fronts. Stirzaker et al. (2005) suggested that the ‘FullStop’ wetting front detector might be the simplest one and is comprised of specially shaped funnel, a filter and a float mechanism. The funnel of the detector is buried in the soil within the root zone of the crop. If sufficient water or rain falls on the soil to move to the funnel, it passes through a filter. This water activates a float mechanism, which operates an indicator flag above the soil surface. The wetting front detectors and a capacitance-type device (the ‘Diviner’ – frequency domain reflectometry) were the best tools (together) to monitor soil water with beans and melons under SDI in the Cowra district of NSW (Stirzaker et al., 2005). The Diviner was useful at identifying
deficits and the wetting front detectors was suitable to identify over irrigation and also useful for nitrate monitoring in leachate.

The EnviroSCAN capacitance probe is widely used to measure soil water content throughout the soil profile and schedule irrigation for orchard crops in Australia. Data are downloaded to monitor water content through the soil profile and to schedule irrigation (Fares and Alva, 2000). One advantage of the Enviroscan is that it enables low cost continuous logging of soil water, which can be useful when it is important to detect infiltration or the flux of water between soil layers over relatively short time periods. A disadvantage is that a very small volume of soil is measured, and there is a relatively large interface between the soil and access tube, so errors can be high. The probes are not useful in cracking soils.

3.2.3. Time domain reflectometer

A TDR emits a pulse charge of electromagnetic energy, using sensors or ‘wave guides’ buried in the soil. The pulse signal reaches the end of the sensor and is reflected back to the TDR control unit. The time taken for the signal to return is related to the water content of the soil surrounding to the probe (Whalley et al., 1994; Charlesworth, 2005). The use of multi-wire probes in the TDR provided rapid determination of soil profile water content and offers the capability of monitoring the dynamics of the soil water volume around a point source to differentiate soil water conditions at different vertical and horizontal soil volumes (Souza and Matsura, 2003). It is, however, expensive.

3.2.4. Neutron probe

The neutron scattering method (neutron probe) measures volumetric water content of soil indirectly using high-energy neutrons emitted from the probe. Neutron probe method is suitable for coarse or medium textured soils but not suitable for measurements near soil
surface and in shallow soils without special calibration (Campbell and Mulla, 1990). The neutron probe has been in use in some sectors of the irrigation industry for many years, and has proven to be suitable for a range of applications from row crops like cotton (Janat and Somi, 2001) to trickle irrigated vegetable crops (Cull et al., 1989). Disadvantages of the neutron probe are the high initial cost, high regulatory requirements (training and licensing), and the need for careful calibration.

In this thesis, tensiometers and gypsum blocks were used to determine soil water potential, and the theta probe was used to measure volumetric water content.

3.3. Water balance approaches in irrigation scheduling

The soil water balance represents the integrated amount of water in the soil at a particular time. The water balance method is an indirect way of monitoring water status, using simplifications of the soil water balance equation. It is used to estimate crop water use (Goldhamer and Snyder, 1989) from climatic data (Allen et al., 1998). Climatic parameters including solar radiation, temperature, relative humidity and wind have either direct or indirect effects on crop water use through their influence on evaporation and transpiration (Howell et al., 1986). Various methods of estimating crop water use from meteorological information are used (Howell et al., 1986). The combination of soil evaporation (E) and transpiration (T) make up the total water use, which is commonly referred to as evapotranspiration (ET). Estimation of evapotranspiration generally uses four factors: reference evapotranspiration (ET₀) based on a specific type of crop, a crop factor (Kcb) that describes both the dynamic seasonal and developmental change in the crop evapotranspiration in relation to ET₀, a soil factor (Kcs) which describes the effect of low soil water content on transpiration and having close relationship with crop growth parameters such as rooting and a soil factor (Ksed), which describes the evapotranspiration
amount from either rainfall or irrigation. The crop water use is represented by the following equation (Allen et al. 1998):

\[
ET_c = ET_r [(K_{cb} K_{cs}) + K_{so}]
\]

Reference evapotranspiration (ET\(_r\)), expressed in mm/day, can be estimated by different methods such as modified Blaney-Criddle method, the modified Jensen-Haise method, the Penman-Monteith combination equation, or directly by pan evaporation. Evaporation pans of various designs have been widely used throughout the world as an index of reference evapotranspiration (ET\(_r\)). To calculate the particular crop water use or crop evapotranspiration, crop coefficient values are used. The crop coefficient (K\(_c\)) value varies between crops and growth stages. Crop evapotranspiration (ET\(_c\)) is calculated by multiplying crop coefficient (K\(_c\)) and reference evapotranspiration (ET\(_r\)) (Qassim and Ashcroft, 2001).

The water balance approach was developed in irrigation to estimate ET from large areas. Its application is difficult under drip irrigation because of the multidimensional water application pattern (Lazarovitch et al., 2007).

3.4. Water use efficiency

Generally, plant growth is directly related to transpiration (T), although under field conditions changes in soil moisture result from both T and soil evaporation (E) (Hillel, 2004). E and T are commonly summed to give evapotranspiration (ET), which can either be measured as change in soil water or estimated as discussed above. Both farmers and scientists are concerned with water use efficiency. In irrigated crops, efficiency of water use can be affected by the method, amount, and timing of irrigation.
Water use efficiency has been defined in various ways and it is important to understand the differences. Loomis (1983) defined it as the ratio of dry matter produced (Y) per unit of water transpired by a crop (T), expressed as kg/mm or kg/ha/mm.

\[ WUE = \frac{Y}{T}. \quad (1) \]

This approach shows the biomass production relative to the water actually used by the plant, and should more correctly be termed the ‘transpiration efficiency’ (TE). The TE of different crops may vary with differences in photosynthetic mechanism (C₃, C₄, and CAM) and vapour pressure deficit (van Keulen, 1975; Lof, 1976).

\[ WUE = \frac{Y_e}{ET} \quad (2) \]

The term \( \frac{Y_e}{ET} \) shows the agronomic yield of the system relative to total water use, and is a more correct use of the term ‘water use efficiency’ or agronomic water use efficiency (Loomis, 1983).

Soil surface modifications such as tillage and retaining surface residue may influence WUE by reducing soil evaporation (E) and increasing crop transpiration (T) (Hatfield et al., 2001). One potential advantage of SDI is reduced soil evaporation (Solomon, 1993).

Loch et al. (2005) described water use efficiency as the amount of water transpired relative to the amount of irrigation applied (t yield/ML water), which could be called irrigation efficiency. He noted that factors such as poor soil structure, profile salinity; and irrigation management that restrict the expansion and efficiency of the plant root system, will all reduce water use efficiency.

Overall agronomic efficiency of water use (\( F_{ag} \)) in irrigated systems is defined by FAO (1997) using an adaptation of the soil water balance:

\[ F_{ag} = \frac{P}{U}, \quad (3a) \]
where $P$ is crop production (total dry matter or the marketable yield) and $U$ is the volume of water applied. The components of $U$ are expressed by the following equation:

$$U = R + D + E_p + E_a + T_w + T_c,$$

where $R$ is the volume of water lost by runoff from the field, $D$ the volume drained below the root zone (deep percolation), $E_p$ the volume lost by evaporation during the conveyance and application to the field, $E_a$ the volume evaporated from the soil surface, $T_w$ the volume transpired by weeds and $T_c$ the volume transpired by the crop. Overall irrigation efficiency is calculated by multiplying the efficiencies of the components. For a system, which includes reservoir storage, water conveyance, and water application, the overall irrigation efficiency is defined as

$$E_o = (E_s) X (E_c) X (E_a),$$

where $E_s =$ reservoir storage efficiency, $E_c =$ water conveyance efficiency, $E_a =$ irrigation application efficiency.

In all agricultural systems, low water use efficiency can occur when soil evaporation is high in relation to crop transpiration, early growth rate is slow (eg. crop establishment stage), water application does not correspond to crop demand, and when shallow roots are unable to utilize deep water in the profile. This was demonstrated by Patel and Rajput, (2007) during the early growth phase of potato. These problems are especially pronounced in intensive vegetable production (Gallardo et al., 1996).

Irrigation control may increase water use efficiency (yield / water used) (Upchurch et al., 1990), water ‘use’ here meaning the sum of ET and deep percolation. The role of irrigation scheduling in improving water use efficiency is considered below.
3.5. Irrigation scheduling to improve water use efficiency

Irrigation scheduling means applying water at intervals based on the needs of the crop, with the primary objective of managing soil water within defined limits. It is the process by which an irrigator determines the timing, amount and quality of water to be applied to the crop (Qassim and Ashcroft, 2001; Bierman, 2005). Scheduling is intended to maximize irrigation application efficiency by minimizing runoff and percolation (drainage) losses (Trimmer and Hanson, 1994).

The range of tools for measuring soil water to use in irrigation scheduling was considered earlier. Whether measured directly, or predicted indirectly using climatic data and crop water use models, soil water status is of primary importance for irrigation scheduling. The use of indirect and direct measurement has often been compared, but it appears that the benefits of each approach are situation-specific and not clear cut. As an example, using direct measurement of soil water to schedule subsurface drip irrigation of tomatoes was no better than using indirect prediction, at least in terms of total fruit yield (Lindsay et al., 1989). However, the direct measurement of soil moisture required significantly less water than indirect prediction. Thus direct measurement of soil water gave higher irrigation efficiency.

Vazquez et al. (2005) illustrate the difficulty with trying to precisely apply irrigation water with drip irrigation. They compared scheduling using crop evapotranspiration ($\text{ET}_c$) with volumetric soil water content measured by TDR, for processing tomato in a silty clay loam. The surface drip had drainage during crop establishment when water was applied at a higher rate than crop evapotranspiration.
Sensors must be placed in the active root zone in proximity to the emitter. Sensor placement in SDI systems varies, but is mostly located midway between emitters (Howell and Meron, 2007).

4. Drip irrigation and its adaptation in sub-surface drip irrigation management

Drip irrigation systems allow water to be applied uniformly and slowly at the plant location so that essentially all the water is placed in the root zone (Johnson et al., 1991).

Drip systems are categorised according to their placement in the field:

- Surface drip irrigation: Water is applied directly to the soil surface.
- Subsurface drip irrigation: Water is applied to below the soil surface through perforated pipes.

Subsurface drip irrigation has been used in Australia and elsewhere for crops including citrus, cotton, sugarcane, some vegetables, sweet corn, ornamentals, lucerne and potato (Raine et al., 2000; Alejandro and Eduardo, 2001; Thorburn et al., 2003; Bhattari et al., 2004; Shock et al., 2004; Lamm and Trooien, 2005). Subsurface drip has proven to be an efficient irrigation method with potential advantages of high water use efficiency, fewer weed and disease problems, less soil erosion, efficient fertilizer application, maintenance of dry areas for tractor movement at any time, flexibility in design, and lower labour costs than in a conventional drip irrigation system. However, there are also potential disadvantages with SDI, which mainly relate to poor or uneven surface wetting and risky crop establishment (Camp et al., 2000; Lamm, 2002; Raine and Foley, 2001).

4.1. Design and installation

Subsurface drip irrigation systems comprise of a filter leading to the main supply tube, sub-main, laterals that convey water to the emitters (Harris, 2005c).
4.1.1. Lateral drip line

Tapes and tubes are available for use as laterals. Tape products are thinner than tubes (Neufeld et al., 1993). Commonly, tube wall thickness ranges from 0.4 mm to 1.5 mm (Hanson et al., 2000). Camp et al. (2000) identified two classes of tape wall thickness. Flexible thin-walled (0.15 mm to 0.30 mm) tapes are typically used for shallow installation, whilst thicker-walled (0.38 mm to 0.50 mm) tapes are installed deeper or where the soil does not provide sufficient support to prevent collapse by equipment or soil weight. O’Neill et al. (2002) used 0.38 mm thickness of tape for potato (Solanum tuberosum L.), corn (Zea mays L.), alfalfa (Medicago sativa) and pinto bean (Phaseolus vulgaris L.) production in sandy loam soils. Successful production of lucerne with sub surface drip irrigation was recorded by Thompson (2005) in Victoria, using 0.38 mm tape.

4.1.2. Tape installation depth

The use of surface versus subsurface drip irrigation varies by region and by crop, and is often based on perceived constraints on the vertical placement of the drip tape/tube or laterals (Clark and Smajstrla, 1996). With SDI, the choice of drip tape depth is influenced by crop, soil, climate characteristics and anticipated cultural practices, but it generally ranges from 0.02 to 0.7 m (Camp, 1998). It is often in the range of 0.05 to 0.2 m for shallow rooted horticultural crops. From the literature, a depth of 0.15 m for lettuce would be appropriate on the sandy soils at UWS, used for experiments later in this thesis.

Although installation depth is generally decided for horticultural reasons, another consideration for determining depth is that deeper placement (0.45 m) will be required if the primary aim is to reduce soil evaporation and capture the potential benefit of improved water use efficiency (yield and quality) that is possible with SDI (Bryla et al., 2003).
With the shallow systems, relatively deeper installation should reduce soil evaporation and also allow for a wider range of cultural practices. However, as noted above, deeper installation may limit the effectiveness of the SDI system for seed germination/crop establishment. Deeply placed drip lines may require an excessive amount of irrigation for germination/crop establishment. This practice can result in off-site environmental effects (Camp, 1998), and it reduces water-use efficiency. Deeper placement may restrict the availability of surface applied nutrients and other chemicals (Camp and Lamm, 2003).

Relatively shallow tape placement has been tried for many years to assist germination (Burt and Styles, 1994). Recent examples include broccoli on sandy loam soil (Roberts et al., 2008) and corn on a silt loam (Lamm and Trooien, 2005). Germination of tomato (Lycopersicon esculentum Mill.) under SDI was better with drip line depths of 0.15 and 0.23 m than at 0.3 m on clay loam soil (Schwankl et al., 1990). It can be assumed that shallow placement is especially important for establishment if there is no supplementary source of surface irrigation.

Shallow placement of drip tape is generally required also for satisfactory growth of shallow rooted crops in sandy soils, which have limited capillary water movement (Broner and Alam, 1996); although this is not always the case, as Rubeiz et al., (1989) found higher zucchini (Cucurbita pepo) yield at 0.15 m depth than 0.04 m depth on a coarse loam soil.

In Australia, tape depth of 0.25 to 0.30 m is used in the Queensland cotton (Gossypium spp.) industry on cracking clay soils (Raine et al., 2000). There are regional differences in the tape placement, with growers in NSW generally installing more deeply than in Queensland (Raine et al., 2000).
4.1.3. Lateral spacing

An overview of published studies shows that lateral spacing ranges from 0.25 to 5 m for SDI, as determined by crop behaviour, cultural practices soil and properties. Wider lateral spacing is practiced in heavy textured soil (Camp, 1998). Closer spacing is recommended for sandy soil (Phene and Sanders, 1976). Lateral spacing is generally one drip line per row/bed or an alternative row/bed with one drip line per bed or between two rows (Lamm and Camp, 2007). With row crops such as tomatoes, laterals are often spaced 1-2 m apart. Lateral spacing of 1.5 m in sub-surface drip-irrigated corn was successful in a silt loam soil (Darusman et al., 1997). Lateral placement of 0.3 m is recommended for subsurface systems in the loamy sand soil of South Carolina for vegetable crops; cowpea (Vigna unguiculata), green bean (Phaseolus vulgaris), yellow squash (Cucurbita pepo), muskmelon (Cucumis melo) and broccoli (Brassica oleracea) (Camp et al., 1993). Lateral spacing of 2 m intervals on a 1:2 drip tape:crop row has been successful in Queensland for cotton (Raine et al., 2000).

The above discussion indicates that closer drip line spacing (0.3 m) and two drip lines per three rows of crop would be appropriate for lettuce on sandy soils in the experiments reported later in this thesis.

4.1.4. Installation

Lateral lines should be laid following the contour of the land as closely as practicable to avoid pressure variations within the line due to elevation change (Haman and Smajstrla, 2003). The first step in installing a successful SDI system is maintaining proper hydraulic design. This allows the system to deal with constraints related to soil characteristics, field size, shape, topography, and water supply.
Lateral diameter and length influence water application uniformity (Kang et al., 1999). Lamont et al. (2002) observed in vegetables in the USA that a tape diameter of 125–200 mm was the industry standard and common for subsurface drip irrigation where rows range from 90 m to 180 m. In Greece, 17 mm polyethylene pipe was used at the shorter row length of 30 m for sugar beet (Beta vulgaris L.) research using subsurface drip (Sakellariou-Makrantonaki et al., 2002).

4.1.5. Emitters

Emitters are plastic devices which precisely deliver small amounts of water. Hla and Scherer (2003) described two types of emitter. Point-source emitters discharge water from individual or multiple outlets. Line-source emitters have perforations, holes, porous walls, or emitters extruded into the plastic lateral lines (Ayars, et al., 2007). Line-source emitters are generally used for widely spaced crops such as vines, ornamentals, shrubs and trees. Point source emitters are used for small fruits, vegetables and closely spaced row crops (Bucks and Davis, 1986). The emitters used for SDI are much the same as those used for surface drip, but the emitter is fixed internally in the drip line (Harris, 2005c).

4.1.6. Emitter spacing

Soil characteristics and plant spacing determine emitter spacing. Spacings used in Queensland are mostly between 0.3 m and 0.75 m for row crops (Harris, 2005d). Kamara et al. (1991) used 0.3 m emitter spacing for drip-irrigated cotton grown in sandy loam soil in the USA. Similarly, an emitter spacing of 0.3 m was suitable for corn production for deep silt loam soils under subsurface drip (Lamm and Aiken, 2005). In a semi-arid environment, 0.45 m emitter spacing was used in clay loam soils for drip-irrigated corn (Howell et al., 1995). In general, emitter spacing should normally be less than the drip lateral spacing and closely related to crop plant spacing (Lamm and Camp, 2007).
4.2. Flushing capacity

A critical area of design that impacts on system performance is the flushing capacity. Many SDI systems appear to have been installed with inadequate flushing capacity, resulting in sediment deposition, decreases in flow volumes and blockages (Pitts et al., 1996). This will produce higher backpressures in the mains, which may also affect system performance (Lamm and Camp, 2007). Retrofitting large valves or increasing the number of valves may solve some flushing problems (Raine et al., 2000).

4.3. Water application uniformity

Water application uniformity in microirrigation depends on system uniformity and spatial uniformity in the field (Wu et al., 2007).

4.3.1. System uniformity

The system uniformity is affected by system design factors such as lateral diameter and emitter spacing (Wu et al., 1986), and manufacturing variation (Bralts et al., 1981a). It is also considered to include emitter clogging (Bralts et al., 1981b). The parameters used to evaluate microirrigation system application uniformity are: the Uniformity Coefficient (UC); emitter flow variation ($q_{var}$); and Coefficient of Variation (CV) of emitter flow (Bralts and Kensar, 1983; Wu et al., 1986). Using these parameters, Ayars et al. (1999) discussed various drip tape products and determined the values of these uniformity parameters. System uniformity values predicted by design or evaluation models are similar for both surface and subsurface drip (Camp et al., 1997).

4.3.2. Spatial uniformity in the field

The spatial uniformity in the field refers to variation in soil water. In addition to system design factors noted above (Wu et al., 2007), it includes variation due to field topography and soil hydraulic properties (Burt and Styles, 1994; Burt et al., 1997).
4.3.3. Causes and consequences of non-uniformity

The causes of non-uniformity include unequal drainage and unequal application rates (Burt, 2004). Even where system uniformity is high, variation in soil properties, such as hydraulic conductivity, can affect drainage and lead to variation in water content. Application uniformity may be directly related to yield (Solomon, 1984b; Letey, 1985). Non-uniformity in one field (45%) was estimated to be mainly due to pressure differences, with only 1% due to unequal drainage and 2% due to unequal application rate (Burt, 2004). Burt (2004) considered the typical manufacturing coefficient of variation in tube today is only 0.02 to 0.06, which will be negligible. Soil ‘excavating’ by subsurface emitters was shown to increase flow rate by 2.8% to 4%, but not sufficiently to affect uniformity calculations (Sadler et al., 1995).

One consequence of non-uniform application is increased drainage (Ben-Asher and Phene, 1993; Phene and Phene, 1987), assuming irrigation for uniformly good crop growth. Drainage may also occur if the application is uniform but the soil water holding capacity or hydraulic properties are not uniform.

Obtaining sufficiently moist soil for germination and crop establishment by applying uniform irrigation to soils which are inherently variable is a challenging issue for SDI (Patel and Rajput, 2007). They found that to provide adequate irrigation water for potato plants in the early growth period, they had to be over-irrigated, leading to more downward movement of water on sandy loam soil than upward capillary movement of water.

4.3.4. Minimising non-uniformity

Overall, minimising non-uniformity of the drip system requires: a design which considers the topography of the field (Wu et al., 2007) periodic checking of the system
(Clark and Phene, 1992), and irrigation scheduling (volume and frequency) (Burt et al., 1997). Greater irrigation uniformity can be achieved by using pressure-compensating emitters in surface and subsurface drip (Schwankl and Hanson, 2007).

Flow meters are widely recommended to check the system performance in subsurface drip irrigation (Alam et al., 2002). They are used to determine the rate and volume of water applied in an automated irrigation control system (Ayars and Phene, 2007).

**4.3.5. Comparison of uniformity in surface and subsurface drip**

In SDI, emitter clogging and accumulation of salt caused by evaporation is less than in surface drip (Hills et al., 1989a). More uniform water content was observed in the root zone with SDI than surface drip (Ghali and Svehlik, 1988). In an SDI system more uniform water content in root zone was observed than surface drip, and thus drainage would be less with SDI (Ben-Asher and Phene, 1993; Phene and Phene, 1987).

**4.4. Management of SDI**

**4.4.1. Discharge rate and irrigation frequency in relation to crop and soil type**

Subsurface drip irrigation systems generally consist of emitters that have discharge rates less than 8 L/hr (ASAE, 2001). A discharge rate of 0.25 L/hr gave high yield of corn in sandy loam soils of Israel (Assouline, 2002), although the difference in yields between discharge rates was not statistically significant. In a silt loam soil a discharge rate of 0.5 L/hr gave the highest onion (*Allium cepa*) yield (Shock et al., 2005). In a drip system, frequency and emitter discharge rate determine the soil water availability and plant water uptake pattern (Coelho and Or, 1996; 1999) and consequently yield (Bucks et al., 1981; El-Gindy and El-Araby, 1996).

Illustrating the importance of matching irrigation frequency to soil type, Ruskin (2005) reported that a coarse textured sandy soil required drip lines with higher flow rates
and shorter irrigation cycles than clay soil. Similarly, shallow rooted vegetable crops on fine sandy soils in Florida required frequent (once or more per day) water application (Haman and Smajstrla, 2002). Conversely, in a clay loam soil, drip irrigation applied every second day achieved maximum tomato yield (Dalvi et al., 1999). High frequency irrigation seems to be especially important for coarser-textured soils, high frequency SDI gave best yields of processing tomato in a sandy loam soil (Ayars et al., 1999) and of potato in loamy soils in China (Wang et al., 2006).

High frequency water application under drip enables maintenance of salts at reasonable levels within the rooting zone (Mmolawa and Or, 2000b).

The main reported benefit of increased irrigation frequency with SDI is the increased yield. A less commonly reported benefit of increased irrigation frequency is improved crop establishment (Phene and Beale, 1976). As crop establishment is a common problem in SDI (considered in detail in Section 4.6), it is surprising that there seem to be relatively few studies of irrigation frequency in relation to establishment. More frequent or pulsing irrigation, which involves applying small increments of water multiple times per day rather than applying large amount for long duration, has been advocated to improve surface and near surface soil moisture wetting for crop establishment (Lamm and Camp, 2007). However, there is a lack of operational guidelines for SDI (Lamm and Camp, 2007). In Australia, a comparison of pulsed and continuous irrigation on a Hanwood loam soil in NSW revealed very little difference between treatments, leading the author to conclude that responses depended on tape depth and soil type (Miller et al., 2000).

Other potential benefits of high frequency SDI are reduced deep drainage of water (Ayars et al., 1999), although for this it will be important to have both uniform application
and uniform soil and crop growth. High frequency SDI may have lower water requirement, as shown by Wendt et al. (1977).

The flow rate of the drip line has to match the particular soil type. When soil hydraulic conductivity decreases, the pressure head of the soil next to the emitter will increase, which reduces the flow rate of emitters (Warrick and Shani, 1996). On the other hand, emitter discharge decreases due to backpressure, which depends on the soil type, possible cavities near the dripper outlet, and the drip system hydraulic properties (Shani et al., 1996). When the pressure in the emitter increases this may significantly reduce the source discharge rate (Lazarovitch et al., 2005).

It was noted earlier in this review that soil types on which intensive horticulture is practised in the Sydney basin vary from uniform sandy alluviums to loam overlying heavy, poorly drained clay. This variation presents a challenge to farmers to match discharge rate to soil type and select appropriate irrigation frequencies, especially when a wide range of crops is grown.

Crop type also influences optimum irrigation frequency, even amongst vegetable crops. For example, on loam soil, cantaloupe (Cucumis melo) yield was higher with weekly irrigations compared to daily irrigations, whilst onion yield was higher for daily irrigation compared with weekly irrigation (Bucks et al., 1981).

In most cases, supplementary irrigation has been used in establishment (eg Schwankl et al., 1993; Howell et al., 1997). Of the many papers dealing with irrigation management with SDI, few appear to have independently varied management for the establishment and growth periods other than adjust the crop factor. It appears that crops are often over-watered in the establishment period (Enciso et al., 2007; Patel and Rajput, 2007) to ensure establishment. This has been reported to increase drainage (Howell et al., 1997).
One topic which appears to have received no study is the need to vary irrigation frequency through the life of a crop to meet different requirements. Frequent irrigation may be needed for good establishment, but frequent irrigation subsequently should reduce deep drainage, and increase water use efficiency. This approach is analogous to securing establishment by increasing irrigation rate above the crop requirement determined by $K_c$ and $ET_r$ (Howell and Meron, 2007), but with less risk of increased drainage.

4.4.2. Fertigation via drip irrigation

Whilst this thesis is not concerned directly with ‘fertigation’, the application of nutrients together with the irrigation water, there are some considerations directly relevant to SDI, so the topic will be briefly reviewed. Fertigation is a sophisticated and efficient method of applying fertilizers with irrigation water (Magen, 1995). It contributes to the achievement of higher yields and better quality by increasing fertilizer efficiency (Haynes, 1985; Imas, 1999), regardless of whether DI or SDI is being used. In addition, minimization of leaching below the root zone may be achieved by fertigation (Hagin and Lowengart, 1996; Hanson, 1996).

Although fertigation can be used with any drip irrigation system, a major potential advantage of subsurface drip is that water and nutrients are potentially used more efficiently when compared to surface installation (Phene et al., 1987). Frequency of fertilizer injection can range from once a week to daily for drip irrigated vegetable crops (Marr, 1993). Combined SDI and nutrient management schemes have been developed for several vegetable crops, including collard, mustard, spinach, and romaine lettuce (Thompson and Doerge, 1995a and b, 1996) and corn (Lamm et al., 2001). Subsurface drip irrigation and fertilizer management together has been found to increase yield on tomato,
sweet corn and cantaloupe (Ayars et al., 1999), sweet corn (Bar-Yosef, 1989), cabbage and zucchini (Rubeiz et al., 1989).

Subsurface drip irrigation provides incremental application of nitrogen and water. With good management, this has been reported to reduce NO₃⁻ leaching and contamination of groundwater in lettuce production (Thompson and Doerge, 1996). For crops such as broccoli, celery and lettuce, N uptake is low in the first half of the season and higher before harvest. Fruiting crops such as tomatoes, pepper and melons require little N until flowering, then increase N uptake, reaching peak uptake during fruit set. These factors need consideration for drip irrigation with fertigation (Hartz, 1996).

Water and fertigation requirements need to be established for each crop, as significant differences occur. For example, watermelon yield may be increased by maximising the interactive effects of water and nitrogen applied through SDI on sandy loam soil (Pier and Doerge, 1995), whereas for broccoli production with SDI on sandy loam soils, fertigation frequency had no effect on yield (Thompson et al., 2002).

Vazquez et al. (2005) observed substantial drainage during the crop establishment period of processing tomato under drip irrigation, when the roots explore only a small volume of soil and water absorption capacity is small (Jackson and Bloom, 1990). The excessive irrigation and associated drainage of tomatoes during establishment caused large N losses (Vazquez et al., 2006). So, if extra irrigation is required to ensure establishment and this creates a risk of drainage, the fertigation regime needs to be varied to minimise the risk of N leaching.

SDI may also manage the placement and availability of immobile nutrients (eg. P). The restricted mobility of the phosphate ion implies that pre-irrigation mixing of P in both clay and sandy soils is necessary, supplemented by addition to the irrigation solution, to
obtain a uniform P concentration in the soil volume (Bar-Yosef and Sheikholeslami, 1976). Immobile nutrients are delivered at the centre of the soil root volume rather than on top of the soil in subsurface drip (Martinez et al., 1991). Fertigation with P in SDI has improved yield, root growth and environmental performance in tomato (Ayars et al., 1999) and sweet corn (Phene et al., 1991).

Potassium is also easily soluble in water and applied through drip irrigation. Phene and Beale, (1976) have shown that daily low rate application of nitrogen and potassium with a high frequency drip irrigation system improved nutrient uptake efficiency of sweet corn in sandy soils and reduced leaching loss.

4.5. Growth and yield of vegetables in surface and sub surface drip irrigation

As a general guide, crops which are suitable for surface drip irrigation are also suited to SDI (Lamm and Camp, 2007). With good agronomic practices, increased yields have been reported for a wide range of crops. These include lettuce (Hanson et al., 1997); sugarbeet (Sharmasarkar et al., 2001; Sakellariou-Makrantonaki et al., 2002); soluble solid content in transplanted muskmelon (Cucumis melo L.) (Hartz, 1997); onion (Hanson and May, 2004; Shock et al., 2004); and green bean (Phaselous vulgaris L.) (Metin-Sezen et al., 2005).

The crop response to SDI differs with crop growth characteristics and rooting pattern (Lamm and Camp, 2007). In lettuce, little yield difference was found between SDI and furrow irrigation in a sandy loam soil (Hanson et al., 1997). Potato yield was increased 27% with SDI over sprinkler irrigation, while reducing irrigation needs by 29%, provided there were drip lines in each crop row (DeTar et al., 1996). SDI had greater yield and higher water use efficiency than surface drip, furrow and sprinkler irrigation with
cantaloupe, zucchini and oranges when irrigation was close to consumptive use (Davis and Pugh, 1974).

Information on root distribution is useful to understand crop responses to irrigation and fertigation, especially with the limited wetted soil volume that develops under subsurface drip (Phene et al., 1991). Phene and Beale (1976) showed that root length and rooted soil volume of sweet corn could be improved by frequent irrigation with shallow SDI. They revealed that frequent irrigation maintained a portion of the root zone within the optimal matric potential range. In high-frequency irrigated corn, root length density and water uptake patterns are determined primarily by the soil water distribution under the drippers, whether the drippers are placed on, or beneath the crop row (Coelho and Or, 1999). Most of the root system is concentrated in the top 40 cm of the soil profile in drip irrigated processing tomatoes (Machado and Oliveira, 2003).

Unfavourable results obtained with drip irrigation have often resulted from inadequate root growth and distribution (Brown and Don Scott, 1984), especially in heavy textured soil (Meek et al., 1983). Supply of aerated water with subsurface drip system can maintain aeration of the root zone in heavy clay soils and significantly increase yield of vegetable soyabean and zucchini (Bhattarai et al., 2004).

Subsurface drip irrigation can minimise the period between crops, especially with reduced tillage, and facilitate more intensive cropping. Multiple cropping with SDI has several practical advantages. The subsurface system does not require staking of the drip tubing during initial plant development, does not interfere with machine or manual thinning, weeding, spraying and harvesting of crops as does surface drip irrigation of vegetable crops (Bucks et al., 1981). A continuous cropping system of head lettuce and cabbage by using no tillage could be a potential advantage with subsurface drip (Chase,
Minimal tillage on semi-permanent beds has been widely adopted in the Sydney region, although not with SDI (Senn and Cornish, 2000).

Multiple cropping of vegetables such as cowpea, green bean, squash, and muskmelon in the spring season and broccoli in the autumn season were possible without yield reduction in a humid area (Camp et al., 1993).

4.6. Problems encountered with SDI

There are potential disadvantages with SDI, including high initial investment cost, clogging of emitters by various means, ‘tunnelling’ of soil, and difficulties with uneven wetting and poor plant establishment (Mizyed and Kruse, 1989; Lamont et al., 2002; Charlesworth, 2005). Qassim (2003) and Harris (2005b) discussed the specific benefits and disadvantages of SDI in Australia:

(1) Crop establishment: In the absence of supplementary irrigation, germination and crop establishment with subsurface drip irrigation depends on unsaturated water movement (i.e. upwards or laterally from the buried emitter). Therefore, important determinants of uniform germination-establishment include the distance from the emitter to the seed/transplant, soil properties (structure, texture, hydraulic conductivity) and preceding water content (Charlesworth and Muirhead, 2003).

(2) Soil and water interaction: According to Lamm (2002), emitter discharge rate can exceed the ability of some soils to distribute the water in the soil. The water pressure in the region around the outside of the emitter may exceed atmospheric pressure thus altering emitter flow. This leads to the “tunnelling” of emitter flow to the soil surface causing undesirable wetting spots in the field. Small soil particles may be carried with the water, causing a ‘chimney effect’ that leads a preferential flow path. The ‘chimney’ may be difficult to permanently remove.
The rest of this section deals with the establishment issue, especially in relation to wetting pattern, which varies with soil type (Brouwer et al., 1990). This is a particular issue for developing SDI for the Sydney Basin because of the wide variation in soil types. Where soil types vary greatly between farms it is both costly and challenging to undertake the research and develop extension recommendations for irrigation design and management that are clear and unambiguous. In fields with heterogeneous soils there can be uneven wetting with its inherent problems.

It was shown earlier in this review that subsurface drip is commonly placed relatively deeply in the soil, even for shallow-rooted horticultural crops, to reduce soil evaporation or to facilitate tillage operations. Consequently, the variable wetting pattern and inadequate surface wetting of subsurface drip irrigation often provides insufficient surface soil moisture to meet the demands of seeds (eg Zimmer et al., 1988) or seedlings.

Several reviews have concluded that crop establishment can be difficult with SDI (Camp et al., 2000; Lamm, 2002; Raine and Foley, 2001), at least for germination of shallow-planted seeds. Harris (2005b) went so far as to say that, in most situations, a crop cannot be established using subsurface drip irrigation alone. If so, then requiring a parallel surface system represents an added cost to SDI, whilst it would also reduce water use efficiency during the period of surface irrigation, and increase the risk of deep drainage.

For cotton, germination remains one of the greatest challenges for subsurface drip irrigation (Raine and Foley, 2001), although the problem extends beyond germination to include the whole establishment period, including establishment from transplanted seedlings. Problems arising from the poor wetting pattern may persist through the growth period of a crop, unless efforts are made to control the wetting pattern and match it to the crop root zone (Bar-Yosef, 1989).
As discussed previously, wetting patterns can be managed by varying dripper discharge rate and spacing (Lubana and Narda, 2001), influencing the dripper interface (Meshkat et al., 2000), increasing irrigation frequency (Phene and Beale, 1976) or amount (Howell and Meron, 2007), and reducing the depth of installation (Patel and Rajput, 2007). It may also be approached through modifying the SDI tape design (Welsh et al., 1995). Accordingly, research has been undertaken to improve crop establishment under SDI following a range of approaches. However, from the literature discussed previously, none of the solutions involving shallow tape installation or higher discharge rates will be satisfactory under all circumstances.

This leaves modification to the drip tape as the most likely approach to achieve satisfactory performance under a wide range of soil and climatic conditions. Even with this, to achieve adequate surface wetting and remove the risk of poor establishment (Zimmer et al. (1988) under all circumstances, it is likely that situation-specific guidelines will be needed for irrigation rate and frequency. Thus for SDI to be adopted in the Sydney region, and to enhance its adoption elsewhere, further research is needed into modification of the drip tape to improve surface wetting, and into development of appropriate guidelines for irrigation rate and frequency.

The modification in SDI design by adding an impermeable membrane has the potential advantages of changing the wetting pattern (Miller et al., 2000) and inhibiting the downward percolation of water (Welsh et al., 1995). To counter problems of poor germination, a new technique was suggested for manipulating the wetting pattern of SDI using an impermeable membrane to transform the point source of water in drip lines to a broad band source from which a capillary force operates to draw water upward and outward (Welsh et al., 1995). Another new subsoil irrigation system consisted of a V-shaped device.
which released foil and pipe simultaneously into the soil (Barth, 1999). Although the impervious layer is intended to reduce downward percolation (Welsh et al., 1995), it is hypothesised here that any benefit may arise because the layer creates a temporary watertable, from which the upward flux of water is increased.

Modifying the drip tape to include the impermeable layer was commercialised in the Capillary Root Zone Irrigation (CRZI) product. It was evaluated in loam and sandy loam soils (Charlesworth and Muirhead, 2003). The results indicated that CRZI provided a more uniform wetting pattern but failed to improve establishment in English spinach. In this case, however, establishment was considered to be good (~50%) with standard subsurface drip because of the particular soil properties that gave rise to adequate surface water. So, despite the improved wetting pattern, germination was no better. The results did show that an impermeable barrier can be beneficial for surface wetting. Similar results have been obtained with lettuce germination (Deery, 2003).

It appears that more research is needed to define the conditions under which the establishment problems arise and to reduce the technical barriers to SDI. Barriers to the adoption of SDI include the need to adapt system design and management to local soil and climatic conditions and constraints.

CRZI has undergone extensive development and is now sold under the trade name Kapillary Irrigation Subsurface System (KISSSTM). The advantage of this product over conventional SDI for vegetable seedling establishment has not been evaluated.
5. Soil properties and SDI performance in the vegetable industry

5.1. Role of soil texture and structure

Hanson et al. (1997) compared furrow, drip and subsurface drip irrigation for lettuce on sandy loam soils. There was more sand and less silt under furrow irrigated plots in the top layer of soil (0-0.3 m) due to greater infiltration than drip plots. Sand, silt and clay contents of the 0-0.3 m depth interval were quite constant with distance in subsurface drip. Changes in clay content, cation levels and the pore space around emitters were observed in long term subsurface drip irrigation with processing tomato, rockmelons and onions (Barber et al., 2001). These authors concluded that these changes could have inhibited the movement of water by altering soil hydraulic properties and reducing the spread of the irrigation wetting-front in clay soils. In one study in heavy textured soil in a region where secondary salinity is a problem, subsurface drip irrigation increased the rate of salinization compared with furrow irrigation because of improved structure and reduced slaking and dispersion in subsoil which led to increased solute movement through the soil profile (Hulugalle et al., 2002).

Slaking and dispersion are used to measure the structural stability of soil (Daniells et al., 2002). Gypsum improves soil structural stability and economic use of gypsum depends on soil properties and seasonal condition (Green and Ford, 1980; Ford et al., 1980). Soil conditioners applied by drip irrigation have also increased water stable aggregation in the wetting zone around the drippers (Shaviv et al., 1987).

Drip irrigation can improve plant water availability in medium and low permeability fine-textured soil, and in highly permeable coarse-textured soil in which water and nutrients move quickly downward from the emitter (Cote et al., 2003). Continuous irrigation at a rate equal to evapotranspiration was optimal for medium textured soils whilst greater application
rate was required for coarse textured soils to minimise deep percolation losses (Ghali and Svehilk, 1988). Many experiments have been conducted in both modelling and field research to investigate plant water availability and root uptake pattern in different soil types (Or, 1996; Or and Coelho, 1996; Mmolawa and Or, 2000 a and b; Thourban et al., 2003).

5.2. Role of soil hydraulic properties

Knowledge of soil hydraulic properties assists design of irrigation systems (Mehta and Wang, 2004). Non-uniformities in hydraulic properties and infiltration rates are considered to be major reasons for inefficiencies in drip irrigation and may cause non-uniformities in soil water content and could potentially affect plant growth. Soil hydraulic conductivity is a limiting factor for water uptake by plants under drip irrigation, particularly in sandy soils (Li et al., 2002). However, in clay loam soils, subsurface drip irrigation resulted in very non-uniform soil water contents above the depth of emitters (Amali et al., 1997), which may be corrected by using a membrane under the drip tube.

5.3. Soil chemical responses to drip and sub-surface drip irrigation

For row crops, the drip emitters are often placed at the centre of row beds, below which most salt loading or leaching would probably occur. In one study, soil electrical conductivity, pH and soluble cations were lower under subsurface drip than surface drip (Nightingale, 1985), suggesting increased leaching. Haynes (1990) observed that the conversion of fertigated ammonium sulphate and urea into nitrate-N caused acidification in the wetted soil volume to the surface (0-20 cm) of silt loam soils, also suggesting an increase in leaching. Similarly, acidification throughout the soil profile was observed in vegetable beds in tomato crops (Stork et al., 2003), again suggesting leaching of NO$_3$. This hypothesis finds support in an investigation of commercial production of processing tomato where subsurface drip irrigation, combined with excessive fertilizer application, was
thought to cause the leaching of nitrogen (and phosphate) to groundwater depths (Stork et al., 2003). Under drip irrigation of tomato crops on sandy loam soils, Vazquez et al. (2005) found that greater drainage occurred during the crop establishment period, which increased the leaching of nitrates previously stored in the soil profile.

From these reports, it seems possible that vegetables crops may be over-irrigated using both subsurface and surface drip. If so, then it may reflect the need to irrigate above crop water requirement in order to maintain acceptable soil moisture in the soil surface, especially in the case of SDI.

5.4. Soil wetting pattern

A basic need for better drip irrigation systems is information about the moisture distribution pattern, shape and volume of soil wetted by an emitter (Levin et al., 1979). The volume of wetted soil represents the amount of water stored in the root zone. Its depth should coincide with rooting depth while its width should be related to the spacing between emitters. One possibility for controlling the wetted volume of a soil is to regulate the emitter discharge rate according to the soil hydraulic properties (Bresler, 1978; Lubana and Narda, 2001).

The wetting front is an important factor in drip infiltration, indicating the boundaries of the wetted soil volume (Bresler, 1978). A simple technique known as the pit method was developed by Battam et al. (2003) for design and management of drip systems.

Soil texture is an unreliable predictor of wetting and for adopting different spacing of emitters. For different soil texture, site-specific information on soil wetting is required (Thorburn et al., 2003). Under given climatic conditions, the effect of soil type on the depth-width-discharge combination is influenced by water holding capacity and hydraulic conductivity of the soil (Zur, 1996).
The wetting pattern with SDI can be affected not only by irrigation management, but also SDI design aspects such as emitter spacing and drip line depth. Dripper function can also be modified after installation. In one study, heterogeneity of the soil in the neighbourhood of a subsurface emitter that had been disturbed by farm equipment resulted in low emitter flow, leading the authors to suggest using soil conditioners to improve and stabilize soil structure around the dripper (Shaviv and Sinai, 2004).

The wetting pattern has also been enhanced by the addition of plastic barriers beneath the drip line (Brown et al., 1996; Charlesworth and Muirehead, 2003).

6. Conclusions

The irrigation industry is under pressure to improve water use efficiency and reduce environmental impacts. In the Sydney region, drip irrigation is not widely used for vegetable production, although it has the potential to improve irrigation performance. From this review, it can be concluded that sub-surface drip might improve water use efficiency, and reduce environmental impact more than surface drip. There would be large benefit for vegetable producers in the Sydney region. It may also overcome two important objections to drip irrigation, the high ongoing cost and the disruption to normal cultural practices.

However, SDI may have significant problems with poor or uneven surface wetting, leading to problems with crop germination and establishment. The research reported in this thesis was undertaken with the broad aim of providing a foundation for the adoption of SDI in the Sydney region, by addressing the problem of risky plant establishment.

Increased irrigation frequency and irrigation amount may improve surface wetting, although in practice, SDI can increase drainage during the establishment period, which
appears to be related to the increased irrigation amount. Shallow tape placement is also helpful, but this has practical limitations due to farm cultural practices.

A promising innovation is the inclusion of a narrow impermeable plastic barrier below the drip line and geotextile layer above the drip line, designed to improve surface wetting. The most recent version of this product has not been evaluated for its effects on surface wetting and crop establishment. Thus there is a need to test whether surface wetting is improved, and also whether this leads to improved establishment.

The research question was:

“Does an impermeable layer beneath the drip tape improve surface soil water conditions and crop establishment compared with conventional SDI?”

As the impermeable layer adds to the cost of SDI, it is also important to know if the modified tape has any benefit that cannot be achieved by varying irrigation rate or frequency, both of which are known to affect wetting patterns but have received little attention in relation to crop establishment.

So, a subsidiary question was:

“Does the modified SDI offer any advantage over using conventional SDI with greater irrigation amount or frequency?”
CHAPTER 3: EFFECTS OF MODIFIED SUBSURFACE DRIP ON LETTUCE CROP ESTABLISHMENT, EARLY GROWTH AND SOIL MOISTURE COMPARED WITH CONVENTIONAL SDI

1. Introduction

The need for improved irrigation systems and practices in the Western Sydney horticultural area was identified in Chapter 2. SDI offers significant potential benefits over conventional drip irrigation, but adoption has been slow because of problems with crop establishment. Poor establishment of seedlings with SDI is due to insufficient surface soil moisture (Zimmer et al., 1988) and subsequent ‘transplant shock’ (Titley, 2000). This is the result of limited upward water movement from the drip line to the soil surface or near the soil surface (Lamm and Camp, 2007), resulting in an uneven supply of water to seeds or seedlings.

Assured establishment with any irrigation system requires consistent management of water and the system infrastructure (Phene, 1996). With SDI, shallow tape installation combined with frequent water application is one approach to improving crop establishment on sandy soil (Burt and Styles, 1994), although there is no general guideline to irrigation frequency. Irrigation application volume during establishment may be increased to more than the requirement estimated by using the crop factor (Howell and Meron, 2007), but this may result in increased deep drainage and reduced water-use efficiency.

An alternative approach is to modify the subsurface drip tape to improve surface soil water. Welsh et al. (1995) introduced ‘Vector flow’ drip line with an impermeable membrane to reduce drainage and encourage longitudinal movement of water. This transformed the drip line from a point source to a broad band source of water and encouraged greater upward

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4 Lettuce is grown commercially from seedlings purchased from nurseries (Dimsey and Vujovic, 2005).
movement of water. This concept was later modified by adding geotextile material above the impermeable membrane (capillary root zone irrigation - CRZI), which facilitated mass flow along the line. This improvement in SDI provided a more uniform wetting pattern than conventional SDI, but it failed to provide an advantage in germination of English spinach (Charlesworth and Muirhead, 2003; Deery, 2003). The CRZI has undergone extensive development and is now sold under a new trade name as KISSSTM.

This Chapter evaluates improvements in soil water and crop establishment with the modified SDI (KISSSTM) compared with conventional SDI. Field experiments were undertaken in autumn and spring. The aim was to determine if an impermeable layer beneath the drip line, and geotextile material above the drip line, improve surface soil water relations and crop establishment with sub surface drip in a sandy soil. A further aim was to determine if the modified SDI was any better for establishment than increasing irrigation frequency or amount with conventional SDI.

2. General methods

2.1. Site location

The experiment was at the University of Western Sydney’s Hawkesbury Campus (UWSH) at Richmond, 64 km west of Sydney, NSW. The experimental site was 33.62° S latitude and 150.75° E longitude at an elevation of 20 m above mean sea level. The mean annual rainfall at the experimental site is 800 mm (Bureau of Meteorology, 2007).

2.2. Soil type

Soil details (after Aiken, 2004) are given in Table 1. The soil type was a Clarendon sand, a freely-draining coarse sand, brownish-grey in colour to a depth of 75 cm, above a
light grey and yellowish brown sandy clay. Parent material of this soil type is coarse sandy alluvium of the Nepean River (Pleistocene).

**Table 1. Soil profile details of the experimental site (after Aiken, 2004)**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Texture description</th>
<th>Colour description</th>
<th>Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-22.5</td>
<td>Coarse sand</td>
<td>Brownish grey</td>
<td>A1</td>
</tr>
<tr>
<td>22.5-55</td>
<td>Coarse sand</td>
<td>Light grey</td>
<td>A2</td>
</tr>
<tr>
<td>55-75</td>
<td>Coarse sandy loam</td>
<td>Light grey and pink mottled</td>
<td>B1</td>
</tr>
<tr>
<td>75-210</td>
<td>Clayey sand</td>
<td>Grey and yellow brown</td>
<td>B2</td>
</tr>
</tbody>
</table>

**2.3. Field preparation**

The field was ploughed and beds formed in a north to south direction. SDI tapes were installed manually in each bed at a nominal depth of 15 cm in each row with lateral spacing of 30 cm. Both drip tape types comprised of 1.6 L h\(^{-1}\) emitters at 50 cm spacing, which is the equivalent application rate of 3.2 L m\(^{-1}\) h\(^{-1}\). An automatic battery operated irrigation controller was installed in the main line of the SDI system.

**2.4. Field layout and general crop culture**

The experiments were randomised complete block designs with 8 replications in Experiment 1, in autumn 2007 (Fig. 1) and 4 replications in Experiment 2, in spring 2007 (Fig. 2). Beds were 6 m long and 1 m wide.

Cos lettuce (*Lactuca sativa*) seedlings were transplanted at 30 cm spacing between plants and rows. There were three rows per bed and two drip lines located between plant rows. Compound fertilizer at 100 kg/ha (12% N, 5.2% P and 14.1% K) was incorporated three days prior to transplanting. Insecticide (Entrust\(^R\) at 60 g/ha) was applied as necessary during plant establishment.
Fig. 1. Field experiment 1 layout

Fig. 2. Field experiment 2 layout
3. Specific methods

3.1. Experiment 1 - Autumn

Crop establishment was observed under two different drip tape types with three irrigation frequencies using equal amounts of water applied to all treatments. The treatments were two drip tape types (T\textsubscript{1}-M.SDI, T\textsubscript{2}-C.SDI) and three irrigation frequencies (1, 2 and 4 times per day designated I\textsubscript{1}, I\textsubscript{2} and I\textsubscript{4}). The amount of water applied was determined by multiplying the previous day’s Class A pan evaporation by a crop factor of 0.4.

Plant numbers were recorded in all plots at 14 days after transplanting (DAT) and percentage establishment was calculated. Leaf number, leaf length and width, and plant fresh weight and dry weight were assessed in each treatment. Four plants were randomly selected immediately after transplanting, tagged and observed for leaf growth parameters during the crop establishment period. The number of leaves was counted daily from 4 to 11 days after transplanting. Lettuce leaf length and width were measured at 7 and 14 days after transplanting. Fresh weight of lettuce was estimated at 14 days after transplanting by harvesting four plants randomly from each bed. The fresh weight samples were dried in a fan-forced dehydrator at 80°C for a minimum of 72 hours to estimate dry weight.

Volumetric soil moisture content was measured daily with a Theta probe (model of ML-2x a Delta T-Device, Measurement Engineering Australia). The measurements were taken twice randomly from the bed at 5-10 cm depth, within 10 minutes after irrigation.

3.2. Experiment 2 – Spring

The spring trial evaluated the modified SDI under a higher evaporative demand. Treatments were the same as in Experiment 1, except that crop factors of 0.4 (A\textsubscript{1}) and 0.8 (A\textsubscript{2}) were also compared to determine if, under a higher evaporative demand, increased
irrigation amount (higher crop factor) provides a wetter soil surface and improved establishment.

Crop establishment was determined 15 DAT by counting all plants. Six plants per plot were randomly selected after transplanting, tagged and observed for leaf number every three days from 3 to 15 DAT. Leaf length and width were measured at 7 and 14 DAT. Plant fresh weight was measured in plants from three locations: the centre of the drip line and on both sides of the drip line. Six plants per location per plot were collected at random and weighed. Volumetric soil water content at 5-10 cm depth was measured during establishment, in the centre and both sides of the drip line, before irrigation.

4. Weather data

Pan evaporation and rainfall were recorded within 100 m of the experimental site. Evaporation data are given in Fig. 3. Evaporation was higher in the spring. Total rainfall of only 4.6 and 1mm was received during the autumn and spring experiments, respectively.

Fig. 3. Pan evaporation for both seasons

5. Statistical analysis of data

Crop establishment data were calculated as percentages and transformed by square root transformation (Steel and Torrie, 1960). Analysis of variance (ANOVA) was
conducted on both experiments using MiniTab ver. 14. Data for leaf appearance in each plot were regressed to calculate the regression coefficient, which is an estimate of leaf appearance rate (LAR). Then LAR was subjected to an ANOVA.

6. Results

6.1. Crop establishment

In both autumn and spring, the mean establishment for M.SDI (100% and 99%) was significantly (p<0.001) greater than for the C. SDI (93% and 97%) (Table 2). In both seasons there was no significant difference between irrigation frequencies. There was also no significant difference due to crop factor in the spring experiment.

Table 2. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on survival (%) of lettuce (14 DAT)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>Autumn M.SDI</th>
<th>C.SDI</th>
<th>I.F.</th>
<th>Spring M.SDI</th>
<th>C.SDI</th>
<th>I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One</td>
<td>10.0</td>
<td>9.6</td>
<td>9.8</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>(99.8)</td>
<td>(92.6)</td>
<td>(96.2)</td>
<td>(98.0)</td>
<td>(98.8)</td>
<td>(97.2)</td>
</tr>
<tr>
<td>Two</td>
<td>10.0</td>
<td>9.6</td>
<td>9.8</td>
<td>9.9</td>
<td>9.9</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>(99.4)</td>
<td>(91.8)</td>
<td>(95.5)</td>
<td>(98.4)</td>
<td>(98.4)</td>
<td>(95.9)</td>
</tr>
<tr>
<td>Four</td>
<td>10.0</td>
<td>9.8</td>
<td>9.9</td>
<td>10.0</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>(100)</td>
<td>(95.9)</td>
<td>(97.8)</td>
<td>(99.2)</td>
<td>(99.6)</td>
<td>(96.6)</td>
</tr>
<tr>
<td>Mean Tape</td>
<td>10.0</td>
<td>9.7</td>
<td>9.9</td>
<td>9.9</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(99.8)***</td>
<td>(93.3)</td>
<td></td>
<td>(98.8)***</td>
<td>(96.6)</td>
<td></td>
</tr>
<tr>
<td>Mean C.F.</td>
<td>0.4 = 9.9 (97.4)</td>
<td>0.8 = 9.9 (97.8)</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at p<0.001, within experiment. Values are square root transformed means. Values in parenthesis have been re-transformed to the original scale.

6.2. Number of leaves

In autumn, M.SDI had significantly more leaves at each time during crop establishment from 4 to 11 days after transplanting (DAT) (Table 3). However, irrigation frequency did not show any significant difference in number of leaves at any time. As no
treatments had been imposed before day 4, the significant difference between tape types must reflect a chance difference in the size of seedlings when they were transplanted although the seedlings were selected at random. Therefore, subsequent differences could not be attributed with certainty to treatment effects. So leaf appearance rate (LAR) was calculated through regression analysis in each treatment over time. An ANOVA was performed on the regression coefficient, which is the LAR (Table 3a). The leaf appearance rate over the establishment period did not show any significant difference due to tape type or irrigation frequency.
Table 3. Leaf number in lettuce during establishment, for two tape types and three irrigation frequencies in autumn 2007

<table>
<thead>
<tr>
<th>Tape type</th>
<th>Day 4</th>
<th>Day 5</th>
<th>Day 6</th>
<th>Day 7</th>
<th>Day 8</th>
<th>Day 10</th>
<th>Day 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.F. 1</td>
<td>6.3</td>
<td>6.5</td>
<td>6.9*</td>
<td>6.9</td>
<td>7.2</td>
<td>7.0*</td>
<td>7.4</td>
</tr>
<tr>
<td>I.F. 2</td>
<td>6.8</td>
<td>6.6</td>
<td>7.1</td>
<td>6.9*</td>
<td>7.8</td>
<td>7.5*</td>
<td>7.8</td>
</tr>
<tr>
<td>I.F. 4</td>
<td>6.4</td>
<td>6.5</td>
<td>6.7</td>
<td>7.2</td>
<td>7.0</td>
<td>7.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Mean</td>
<td>6.1</td>
<td>6.2</td>
<td>6.3</td>
<td>6.6</td>
<td>6.8</td>
<td>6.8</td>
<td>7.2</td>
</tr>
</tbody>
</table>

* Significant at p<0.05

Table 3a. Lettuce leaf appearance rate during crop establishment (leaves per day) for two tape types and three irrigation frequencies in autumn 2007

<table>
<thead>
<tr>
<th>Tape type</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.SDI</td>
<td>0.44</td>
<td>0.36</td>
<td>0.45</td>
<td>0.41</td>
</tr>
<tr>
<td>C.SDI</td>
<td>0.38</td>
<td>0.39</td>
<td>0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>Mean</td>
<td>0.41</td>
<td>0.38</td>
<td>0.42</td>
<td>NS</td>
</tr>
</tbody>
</table>

NS – Not Significant.
In the spring experiment, leaf numbers in the M.SDI were significantly greater than in the C.SDI during the crop establishment period from 3 to day 15 DAT (Tables 4a to 4e).

Irrigation frequency initially had no effect on leaf number, but by the end of the crop establishment period, leaf numbers were significantly higher in the treatment with most frequent irrigation.

Leaf numbers were consistently higher with the higher crop factor.

Table 4a. Number of leaves on day 3 (spring 2007)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean IF</th>
<th>Mean C.F. x I.F.</th>
<th>Mean Tape x IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>6.5</td>
<td>6.8</td>
<td>5.8</td>
<td>6.5</td>
<td>6.4</td>
</tr>
<tr>
<td>0.8</td>
<td>6.4</td>
<td>6.8</td>
<td>6.3</td>
<td>6.3</td>
<td>NS</td>
</tr>
<tr>
<td>Mean</td>
<td>6.4 *</td>
<td>6.2</td>
<td>6.2 *</td>
<td>6.5</td>
<td>NS</td>
</tr>
<tr>
<td>C.F. x Tape</td>
<td>6.2</td>
<td>6.7</td>
<td>6.1</td>
<td>6.2</td>
<td>NS</td>
</tr>
</tbody>
</table>

The main effect of tape type and the CF x IF interaction were significant.

* Significant at p< 0.05, NS – not significant

Table 4b. Number of leaves on day 6 (spring 2007)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean IF</th>
<th>Mean C.F. x I.F.</th>
<th>Mean Tape x IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>8.1</td>
<td>8.3</td>
<td>6.8</td>
<td>8.1</td>
<td>7.8</td>
</tr>
<tr>
<td>0.8</td>
<td>7.9</td>
<td>8.0</td>
<td>7.5</td>
<td>7.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Mean</td>
<td>8.1 **</td>
<td>7.5</td>
<td>7.7 NS</td>
<td>8.0</td>
<td>8.3</td>
</tr>
<tr>
<td>C.F. x Tape</td>
<td>8.0</td>
<td>8.3</td>
<td>7.4</td>
<td>7.7</td>
<td>NS</td>
</tr>
</tbody>
</table>

The main effect of tape type was significant.

** Significant at p< 0.01, NS – not significant
Table 4c. Number of leaves on day 9 (spring 2007)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean IF</th>
<th>Mean C.F. x I.F.</th>
<th>Mean Tape x IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>One</td>
<td>11.5</td>
<td>11.8</td>
<td>10.1</td>
<td>11.5</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>10.9</td>
<td>11.1</td>
<td>11.3</td>
<td>10.9</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>11.4</td>
<td>12.6</td>
<td>11.1</td>
<td>11.1</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Mean</td>
<td>11.5</td>
<td>11.0</td>
<td>11.1</td>
<td>11.5</td>
<td>NS</td>
</tr>
</tbody>
</table>

The main effect of tape type and the interaction between CF x IF were significant.
* Significant at p<0.05, 0.01 respectively, NS – not significant.

Table 4d. Number of leaves on day 12 (spring 2007)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean IF</th>
<th>Mean C.F. x I.F.</th>
<th>Mean Tape x IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>One</td>
<td>13.5</td>
<td>14.0</td>
<td>12.2</td>
<td>13.3</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>12.9</td>
<td>13.3</td>
<td>13.1</td>
<td>12.8</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>13.6</td>
<td>14.8</td>
<td>12.9</td>
<td>13.1</td>
<td>13.6**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.3</td>
</tr>
<tr>
<td>Mean</td>
<td>13.7</td>
<td>12.9</td>
<td>13.1</td>
<td>13.5</td>
<td>NS</td>
</tr>
</tbody>
</table>

The main effect of tape type, and the interactions between CF x IF and Tape x IF were significant.
*, **, *** Significant at p< 0.05, 0.01, 0.001 respectively.

Table 4e. Number of leaves on day 15 (spring 2007)

<table>
<thead>
<tr>
<th>IF (irrig./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean IF</th>
<th>Mean C.F. x I.F.</th>
<th>Mean Tape x IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>One</td>
<td>15.2</td>
<td>15.8</td>
<td>14.1</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>14.7</td>
<td>15.8</td>
<td>14.8</td>
<td>14.8</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>15.4</td>
<td>16.7</td>
<td>14.6</td>
<td>15.1</td>
<td>15.4 **</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.0</td>
</tr>
<tr>
<td>Mean</td>
<td>15.6</td>
<td>14.7</td>
<td>14.8</td>
<td>15.5</td>
<td>NS</td>
</tr>
</tbody>
</table>

All main effects and interactions were significant.
* Significant at p< 0.05, 0.001, respectively.
The LAR over the establishment period in spring was significantly greater (p<0.05) with the M.SDI, higher crop factor, and more frequent irrigation (Table 5). The interaction between tape type and irrigation frequency, tape type and crop factor were also significant (p<0.05). The LAR with M.SDI was 0.80 leaves/day, compared with conventional SDI at 0.74 leaves/day (p<0.001). The greatest LAR (0.84 leaves/day) was with the M.SDI and highest frequency of irrigation.

Table 5. Leaf appearance rate (leaves per day) during crop establishment for tape type, irrigation frequency and crop factor (spring 2007)

<table>
<thead>
<tr>
<th>IF (Irri./day)</th>
<th>M.SDI 0.4</th>
<th>M.SDI 0.8</th>
<th>C.SDI 0.4</th>
<th>C.SDI 0.8</th>
<th>I.F. Mean</th>
<th>Mean Tape x I.F. Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>0.76</td>
<td>0.80</td>
<td>0.72</td>
<td>0.74</td>
<td>0.76</td>
<td>0.78</td>
</tr>
<tr>
<td>Two</td>
<td>0.74</td>
<td>0.80</td>
<td>0.76</td>
<td>0.75</td>
<td>0.76</td>
<td>0.77</td>
</tr>
<tr>
<td>Four</td>
<td>0.81</td>
<td>0.87</td>
<td>0.72</td>
<td>0.77</td>
<td>0.79</td>
<td>0.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C.F. x Tape</th>
<th>Mean Tape</th>
<th>Mean C.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.80 ***</td>
<td>(CF 0.4) 0.75 **</td>
</tr>
<tr>
<td>Mean Tape</td>
<td>0.74</td>
<td>(CF 0.8) 0.79</td>
</tr>
<tr>
<td>Mean C.F.</td>
<td>(CF 0.4) 0.75 **</td>
<td>(CF 0.8) 0.79</td>
</tr>
</tbody>
</table>

The main effects of tape type and IF, and the interaction between Tape type x IF, CFxTape type were significant. *, **, *** Significant at p< 0.05, 0.01, 0.001 respectively.

6.3. Leaf size

Leaf length

Comparing tape types, the M.SDI had greater leaf length at both 7 and 14 DAT (p<0.001) in the autumn experiment (Table 6). The effect of irrigation frequency (p<0.001) and interaction between tape type and irrigation frequency (p<0.01) were significant at 7 DAT. Four irrigations per day in M.SDI recorded the greatest leaf length at 7 DAT (7.5 cm). At 14 DAT, the effect of irrigation frequency was again significant (p<0.001). The interaction between tape type and irrigation frequency was not significant (p<0.05).
Table 6. The effect of tape type and irrigation frequency (IF) on leaf length (cm) at 7 and 14 days after transplanting (autumn 2007)

<table>
<thead>
<tr>
<th>Tape type</th>
<th>7 DAT</th>
<th>14 DAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigation frequency/day</td>
<td>Tape Mean</td>
</tr>
<tr>
<td>M.SDI</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6.8</td>
<td>6.9</td>
<td>7.5</td>
</tr>
<tr>
<td>C.SDI</td>
<td>6.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Mean IF</td>
<td>6.6</td>
<td>6.7</td>
</tr>
</tbody>
</table>

The main effects of both tape type and IF were significant at 7 and 14 DAT, and the tape x IF interaction at 7 DAT. *, ***, Significant at p<0.05, p<0.001

A similar trend was observed in the spring experiment. The M.SDI system had greater leaf length (p<0.01) at both 7 DAT (Table 7) and 14 DAT (Table 8). The effect of irrigation frequency was significant (p<0.001) at 7 DAT (Table 7) and 14 DAT (Table 8), with four/irrigations per day resulting in the greatest leaf length. The interaction between tape type and irrigation frequency was significant at 7 DAT, but not at 14 DAT. Crop factor had no significant effect on leaf length at 7 DAT, but it was significant at 14 DAT.

Table 7. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on leaf length 7 days after transplanting (spring 2007)

<table>
<thead>
<tr>
<th>IF (Irr./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean I.F.</th>
<th>Mean Tape x I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
<td>0.4</td>
<td>8.4</td>
<td>8.3</td>
</tr>
<tr>
<td>One</td>
<td>8.3</td>
<td>8.4</td>
<td>8.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Two</td>
<td>8.5</td>
<td>8.4</td>
<td>8.1</td>
<td>8.3</td>
</tr>
<tr>
<td>Four</td>
<td>8.8</td>
<td>8.9</td>
<td>8.6</td>
<td>8.7</td>
</tr>
<tr>
<td>Mean</td>
<td>8.5 NS</td>
<td>8.4</td>
<td>8.5</td>
<td>8.4</td>
</tr>
</tbody>
</table>

The main effects of both tape type and IF were significant. *, **, ***, Significant at p<0.05, 0.01, 0.001 respectively
Table 8. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on leaf length 14 days after transplanting (spring 2007)

<table>
<thead>
<tr>
<th>IF</th>
<th>M.SDI 0.4</th>
<th>M.SDI 0.8</th>
<th>C.SDI 0.4</th>
<th>C.SDI 0.8</th>
<th>Mean I.F.</th>
<th>Mean Tape x I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>9.3</td>
<td>9.6</td>
<td>9.3</td>
<td>9.3</td>
<td>9.3</td>
<td>9.4</td>
</tr>
<tr>
<td>Two</td>
<td>9.5</td>
<td>9.5</td>
<td>9.0</td>
<td>9.1</td>
<td>9.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Four</td>
<td>9.7</td>
<td>10.1</td>
<td>9.4</td>
<td>9.5</td>
<td>9.7</td>
<td>9.9</td>
</tr>
</tbody>
</table>

C.F. x Tape

<table>
<thead>
<tr>
<th>Mean</th>
<th>9.5</th>
<th>9.7</th>
<th>9.2</th>
<th>9.3</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Tape</td>
<td>9.6</td>
<td>**</td>
<td>9.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean C.F. | 9.4 (0.4) | *** | 9.5 (0.8) |

All main effects and the interaction between tape type and CF were significant.
***, ** Significant at p< 0.01, 0.001 respectively

Leaf width

Values for leaf width are shown using interval plots to reveal the greater variability of the C.SDI (Fig. 4). With respect to treatment responses, in autumn, leaf width of 3.0 cm at 7 DAT for M.SDI was significantly greater (p<0.001) than in conventional SDI with 2.8 cm. Four irrigations per day recorded 3.0 cm leaf width, which was greater than in less frequent irrigations (Fig. 4). The interaction between tape type and irrigation frequency was significant (p<0.001) at 7 DAT. The same trends were observed at 14 DAT.

Fig. 4. Effects of tape type and irrigation frequency on lettuce leaf width during autumn 2007
In the spring experiment leaf width was greater than in autumn, at both 7 and 14 DAT. In both observations, the mean leaf width for M.SDI (3.4 cm and 4.0 cm) was significantly greater than conventional SDI (3.3 cm and 3.9 cm) respectively. Compared to three irrigations per day, plants receiving four irrigations per day recorded 3.5 cm and 4.0 cm width at 7 and 14 DAT, respectively. Crop factor did not show any significant difference at 7 DAT, whilst at 14 DAT it was significant (p<0.001). The interaction between tape type and irrigation frequency was statistically significant (p<0.05) at 7 DAT, but not at 14 DAT.

![Interval Plot of Lettuce Leaf Width at 7 and 14 DAT during spring 2007](image)

**Fig. 5. Effects of tape type and irrigation frequency on lettuce leaf width during spring 2007**

**6.4. Lettuce fresh weight**

In the autumn experiment, plants in the M.SDI treatment had significantly (p<0.001) higher fresh weight (19.2 g/plant) than C.SDI (16.6 g/plant) (Table 9). More frequent irrigation (four/day) gave greater fresh weight of 20.4 g/plant (p<0.001) than less frequent irrigation. The interaction between tape type and irrigation frequency was not significant.
Table 9. The effects of tape type and irrigation frequency (IF) on fresh weight (g/plant) at 14 DAT (autumn 2007)

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Tape type</th>
<th>Mean I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One</td>
<td>17.4</td>
<td>14.2</td>
</tr>
<tr>
<td>Two</td>
<td>18.6</td>
<td>16.4</td>
</tr>
<tr>
<td>Four</td>
<td>21.6</td>
<td>19.1</td>
</tr>
<tr>
<td>Mean</td>
<td>19.2 ***</td>
<td>16.6</td>
</tr>
</tbody>
</table>

*** Significant at p< 0.001

In the spring experiment, the overall plant growth was greater in M.SDI than C.SDI (p<0.001) (Table 10). The crop factor of 0.8 gave significantly higher fresh weight of 21.9 g/plant (p<0.001) compared with the 0.4 crop factor (17.2 g/plant). Significant increases in lettuce fresh weight in response to irrigation frequency were evident. The interaction between tape type and irrigation frequency was significant (p<0.01), with four irrigations per day and the M.SDI giving the highest fresh weight of 25.0 g/plant.

Table 10. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on fresh weight (g/plant) at 14 DAT (spring 2007)

<table>
<thead>
<tr>
<th>IF (Irri./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean I.F.</th>
<th>Mean Tape x I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
<td>0.8</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>One</td>
<td>17.3</td>
<td>21.4</td>
<td>12.9</td>
<td>18.6</td>
</tr>
<tr>
<td>Two</td>
<td>18.2</td>
<td>23.6</td>
<td>14.9</td>
<td>19.5</td>
</tr>
<tr>
<td>Four</td>
<td>22.4</td>
<td>27.6</td>
<td>17.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Mean</td>
<td>19.3</td>
<td>24.2</td>
<td>15.1</td>
<td>19.5 ***</td>
</tr>
<tr>
<td>C.F. x Tape</td>
<td></td>
<td></td>
<td></td>
<td>*** **</td>
</tr>
<tr>
<td>Mean Tape</td>
<td>21.7</td>
<td></td>
<td>17.3</td>
<td></td>
</tr>
<tr>
<td>Mean C.F.</td>
<td>(0.4 C.F) 17.2 ***</td>
<td>(0.8 C.F) 21.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**, *** Significant at p< 0.01, 0.001 respectively
Plant fresh weight responded to the plant’s position in relation to the drip tape. Fresh weight in the conventional SDI varied significantly (p<0.05) between positions, with weight being greater in the centre of the bed between two drip lines (19.2 g/plant) compared with either side of the drip line (16.2 and 16.6 g/plant) (Table 11). The M.SDI had uniform growth of plants across all positions.

**Table 11. The effect of plant position, in relation to the drip line, on lettuce fresh weight (g/plant) at 14 DAT (spring 2007)**

<table>
<thead>
<tr>
<th>Plant position</th>
<th>M.SDI</th>
<th>C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One side of drip line</td>
<td>21.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Centre of 2 drip lines</td>
<td>22.0</td>
<td>19.2</td>
</tr>
<tr>
<td>Other side of drip line</td>
<td>21.6</td>
<td>16.6</td>
</tr>
<tr>
<td>Mean</td>
<td>NS</td>
<td>***</td>
</tr>
</tbody>
</table>

*** Significant at p< 0.001

**6.5. Lettuce dry weight**

In the autumn experiment, plant dry weight increased at the greatest irrigation frequency (4/day), with mean values increasing from 1.6 g/plant to 2.0 g/plant (p<0.001) from one irrigation per day to four irrigations per day (Table 12). The mean weight in the modified SDI treatment was 1.8 g/plant, which was significantly greater than the 1.6 g/plant in the conventional SDI (p<0.001). The interaction between tape type and irrigation frequency was not significant (p>0.05).

**Table 12. The effect of tape type and irrigation frequency on dry weight (g/plant) at 15 DAT (autumn 2007)**

<table>
<thead>
<tr>
<th>Tape type</th>
<th>Irrigation frequency/day</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>M.SDI</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>C.SDI</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Mean</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

*** Significant at p<0.001
Plant dry weight in the spring experiment responded similarly to the autumn experiment, with the main effects of tape type and irrigation frequency both being highly significant (Table 13). However, in the spring experiment, the interaction between tape type and irrigation frequency was also significant (p< 0.001). In addition, the main effect of irrigation amount (crop factor) was significant (p< 0.001).

Table 13. The effects of tape type, irrigation frequency (IF) and crop factor (CF) on dry weight (g/plant) (spring 2007)

<table>
<thead>
<tr>
<th>IF (Irri./day)</th>
<th>M.SDI</th>
<th>C.SDI</th>
<th>Mean I.F.</th>
<th>Mean Tape x I.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>One 0.4</td>
<td>1.5</td>
<td>0.4</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>One 0.8</td>
<td>1.9</td>
<td>0.8</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Two 0.4</td>
<td>1.6</td>
<td>1.2</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Two 0.8</td>
<td>1.7</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Four 0.4</td>
<td>1.9</td>
<td>1.4</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Four 0.8</td>
<td>2.1</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>

All main effects and the tape x IF interaction were significant.

Table 14. The effect of plant position, in relation to the drip line, on lettuce dry weight (g/plant) at 15 DAT (spring 2007)

<table>
<thead>
<tr>
<th>Plant Position</th>
<th>M.SDI</th>
<th>C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One side of drip line</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Centre between 2 drip lines</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Other side of drip line</td>
<td>1.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Mean NS *

* Significant at p<0.05

6.6. Volumetric soil water content

Volumetric soil water content, measured after irrigation in the autumn trial, responded significantly to tape type and irrigation frequency (Table 15). Soil in the
modified SDI treatment was wetter than in conventional SDI at both times of measurement. The effect of irrigation frequency was also significant.

**Table 15. The effects of tape type and irrigation frequency on volumetric soil water content (v/v) during establishment (autumn 2007) (after irrigation)**

<table>
<thead>
<tr>
<th>Tape type</th>
<th>First week after treatment commenced</th>
<th>Second week after treatment commenced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigation frequency/day 1 4 Mean</td>
<td>Irrigation frequency/day 1 4 Mean</td>
</tr>
<tr>
<td>M.SDI</td>
<td>0.192 0.246 0.219*</td>
<td>0.180 0.251 0.215*</td>
</tr>
<tr>
<td>C.SDI</td>
<td>0.175 0.201 0.188</td>
<td>0.164 0.204 0.184</td>
</tr>
<tr>
<td>Mean</td>
<td>0.183 0.223**</td>
<td>0.172 0.228***</td>
</tr>
</tbody>
</table>

*, **, *** Significant at p<0.05, 0.01, 0.001 respectively

In the spring trial, the volumetric soil water content before irrigation responded to crop factor, tape type and irrigation frequency (Table 16). The M.SDI had higher water content (0.05 v/v) than conventional SDI (0.04 v/v). The highest soil water content (0.09 v/v) was recorded in the M.SDI with 0.8 C.F. and four irrigations per day.

**Table 16. The effect of tape type, irrigation frequency (IF) and crop factor (CF) on soil water content (v/v) during establishment (spring 2007) (before irrigation)**

| IF (Irri./day) | M.SDI 0.4 0.8 | C.SDI 0.4 0.8 | Mean I.F. Mean C.F. x I.F. Mean Tape x IF |
|----------------|---------------|---------------|----------------|----------------|----------------|
| One            | 0.016 0.026 0.013 0.038 | 0.023 0.015 0.032 | 0.021 0.025 |
| Four           | 0.049 0.088 0.038 0.067 | 0.060 0.045 0.077 | 0.068 0.053 |
| Mean Tape      | 0.045 *** 0.039 *** | ***  *** |
| Mean C.F. (0.4 0.8) Mean C.F. x Tape | 0.032 * 0.057 0.026 0.053 |

All main effects and interactions were significant
*, *** Significant at p<0.05, 0.01 respectively

There was a significant effect of emitter position on soil water content, but only in the C. SDI (p<0.01) (Table 17). Higher water content was observed between the drip lines (0.041 v/v) than to either side of them (0.038 v/v).
Table 17. The effect of emitter position on soil water content (v/v) (spring, 2007) (before irrigation)

<table>
<thead>
<tr>
<th>Plant position</th>
<th>M.SDI</th>
<th>C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One side of drip line</td>
<td>0.045</td>
<td>0.038</td>
</tr>
<tr>
<td>Centre between two drip lines</td>
<td>0.044</td>
<td>0.041</td>
</tr>
<tr>
<td>Other side of drip line</td>
<td>0.045</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Mean NS **

** Significant at p< 0.01, NS – Not Significant

7. Discussion

7.1. Overall performance

Subsurface drip irrigation (SDI) offers many potential advantages to vegetable growers, but the adoption of SDI has been slow, partly because of increased risk of poor establishment which is related to poor or uneven surface wetting (DeTar, 2004). The two field experiments reported here suggest that modifying SDI with an impermeable layer beneath the drip tape and geotextile above the drip has the potential to improve surface soil water, plant establishment and early growth.

In general, lettuce establishment presently requires surface irrigation to supplement SDI (Harris, 2005a). The shallow rooted lettuce has shown uneven establishment during conditions of environmental stress, and it is highly influenced by irrigation management. Seedling establishment is one of the most critical stages of lettuce growth (Titley, 2000). These considerations suggest that SDI would not be suitable for lettuce. However, the results obtained from the M.SDI (KISSS™) improved soil water, crop establishment and growth compared to C.SDI.

These results were achieved under both low and relatively high evaporative demand (in autumn and spring) and on light-textured soil which has traditionally presented the greatest difficulties for SDI (Li et al., 2002). On the basis of these results,
the modifications to SDI evaluated here do address the main concern with using SDI for vegetables such as lettuce, that is, the poor establishment.

Although the differences in mortality were relatively small, they appear to reflect a lower level of stress in the plants following transplanting, and this resulted in improved growth. Plants in the modified SDI had higher leaf appearance rates (at least in spring), wider and longer leaves, and ultimately had higher fresh and dry weights at the end of the establishment period (15 DAT). The measurements of soil water revealed wetter conditions at the soil surface with the modified SDI.

7.2. Comparison between the types of SDI

In both experiments, the modified SDI system resulted in better survival of the transplanted seedlings. Whilst the difference was numerically small at an average of 99% for M.SDI and 95% for the conventional SDI, it indicated a superior environment for establishment in the M.SDI system.

This superior environment was reflected in higher leaf appearance rates in the spring experiment. In both experiments, leaves were longer and wider. Leaf appearance rates were higher in the spring experiment than in autumn, presumably reflecting the higher temperatures. In direct seeded lettuce, Thompson and Goerage (1996) reported a leaf appearance rate of 1-2 leaves/day at 19 days after sowing, which is higher than in either of the two field experiments reported here, but this may reflect differences in temperature. For transplanted seedlings in Australia, Montagu et al. (1998) reported leaf numbers that were comparable to the crops reported here.

Plant fresh and dry weights were substantially greater with the M.SDI with increases in fresh weight over the conventional SDI of 16% and 25% in the autumn and spring experiments, respectively.
A further advantage of the modified SDI system was that plants were more uniform. If the differences present at 15 DAT were carried through to maturity, this would mean more uniform sizes and harvest dates, which would be a significant advantage for marketing (Bogle and Hartz, 1986). With plants harvested in the vegetative stage, it is usual for differences established early in development to continue through until harvest (Karam et al., 2002). Whilst delaying harvest of smaller plants may result in more comparable plant weights, this is undesirable as it increases the duration of harvest and harvest costs. In some plants, a delay will mean plants progress into reproductive development and are not harvestable.

The improved establishment and growth in the M.SDI system was very likely due to improved plant water status rather than any other factor, although only soil water was measured. In the autumn experiment, soil water content in the surface soil after irrigation averaged 21.7% in the modified SDI compared with 18.6% in the conventional SDI. The difference between the tape types was greatest with the high irrigation frequency (4/day), in which soil water content was 5% higher than with the conventional SDI.

In the spring experiment, the soil water was measured just before irrigation began as a measure of the driest conditions, or the maximum stress, that newly transplanted seedlings might have encountered. The difference between the tape types overall was small, although statistically significant. Soil in the modified SDI was consistently wetter than with the conventional SDI at comparable irrigation frequencies and crop factors (irrigation amounts).

The best evidence that the improved growth of the M.SDI was related to improved surface water lies in the close relationship between plant weight and soil
water, regardless of the source of variation in soil water: tape type, crop factor, or irrigation frequency, or location within the plot.

The finding that an impermeable layer under the SDI improved surface water confirms the earlier finding of Charlesworth and Muirhead (2003) and Deery (2003) using an early version of M.SDI (‘CRZI’), and extends it to lighter-textured soil. Also, these authors found no horticultural benefit from the improved surface water with the modified SDI. This was because, even with the poor wetting of the C.SDI, crop establishment and growth in their experiments was satisfactory given the hydraulic properties of the particular soil.

Whilst the present experiments establish that the new modified SDI (KISSSTM) is superior to C.SDI, it does not establish whether product development since the original modified SDI product (CRZI) is responsible for the improved performance. However, Welsh et al. (1995), Brown et al. (1996) and Barth (1999) all provide evidence that an impermeable layer that inhibits drainage will improve surface wetting of SDI. Any additional advantage of M.SDI (KISSSTM) may lie in the geotextile fabric which has now been included. This will presumably hold more water against drainage and prolong any upward flux to the soil surface.

7.3. Responses to crop factor and irrigation frequency

Plants responded to both increased crop factor (CF), that is increased irrigation amount, and irrigation frequency (IF). However, for every combination of CF and IF, the growth of plants with the modified SDI (KISSSTM) was greater than with conventional SDI. The modified SDI was as effective in improving surface soil water, compared with conventional SDI, as increasing irrigation amount and frequency. Under
any combination of irrigation frequency or crop factor, the modified SDI (KISSSTM) was better than the conventional SDI.

The response to irrigation frequency is summarised using regression analysis in Fig.6. Not only did the M.SDI have the greater plant weight overall, but the response to irrigation frequency was greater than with the C.SDI. The greater response to increased irrigation frequency in the M.SDI cannot be explained with certainty, but it is likely that with smaller volumes of water applied in each irrigation, there is increasing probability of all of the water being retained above the impermeable layer, within the geotextile.

![Graphs showing plant fresh weight response to irrigation frequency in M.SDI and C.SDI systems](image_url)

**Fig. 6. Plant fresh weight response to irrigation frequency in modified SDI (left) and conventional SDI (right)**

Other studies have shown that short, frequent pulses of water are required to maintain optimal soil water regime on sandy soils (Ghali and Svehlik, 1988). Greatest efficiency of water use was found at frequent intervals with drip irrigation (Freeman, 1976). Similarly, more frequent water application through SDI produced better results in vegetable production (El-Gindy and El-Araby, 1996). Thus more frequent irrigation has been shown to improve lettuce performance (Silber et al., 2003). One guiding principle in micro-irrigation on sandy soils is to water frequently for good establishment, possibly four irrigations per day (Lantzke, 2007).
Although the response to irrigation frequency reported here is consistent with other studies, it appears to be the first to show this effect in a modified SDI system, and that the M.SDI responded more to the greater irrigation frequency. It is significant that, despite the improved surface water status with the modified SDI (Tables 15, 16) and Fig. 6\(^5\), further improvements were possible with increased irrigation frequency (whilst providing the same amount of irrigation overall).

The data for soil water are consistent with the hypothesis that a fraction of the water applied at each irrigation is retained in a temporary water table which forms along the drip tape, above the impermeable layer of the modified SDI, at least in the KISSSTM product in which geo-textile has been included. According to Hillel (1972), a water table will increases upward flux of water towards the soil surface. This benefit will persist after irrigation until the water table has been depleted. The greater the frequency of irrigation in a period of time, the more of the total irrigation water applied that is available for transfer from the water table to the soil surface for evapotranspiration, and the less is available for drainage.

In the spring experiment when evaporative demand was relatively high (5.8 mm/day), both soil water and plant weight in the modified SDI system responded to increasing the amount of irrigation water applied. The implication is that even with the modified SDI (KISSSTM), soil water may limit crop establishment under high evaporative demand, unless the crop is over-watered. Frequent irrigation may not be adequate, despite the benefit under these conditions (Fig. 6). That is, there appears to be an additional advantage in scheduling or regulating irrigation by using a higher crop

\(^5\) Compare one irrigation/day in M.SDI with four/day in C.SDI
factor (0.8) than the low leaf area of transplants would suggest (Howell and Meron, 2007).

Where it is imperative to reduce drainage and improve irrigation efficiency, the modified SDI (KISSSTM) offers distinct advantages over the conventional SDI, even if more frequent irrigation may be required.

8. Summary of the results

Generally the modified SDI performed better than the conventional SDI in both seasons. For shallow rooted crops like lettuce, the modified SDI had a positive effect on soil moisture and plant performance. The soil water response was consistent with the hypothesis that creating a localised water table encourages upward capillary water movement, maintaining more favourable conditions in the root zone. The crop establishment, leaf appearance rate, leaf size and plant fresh weights were all higher in the modified SDI than conventional SDI. Frequent irrigation in the modified SDI further improved lettuce establishment in sandy soil. Under more extreme evaporative demand, it may be necessary to increase the amount of irrigation water applied. Whether this is required or not, it is clear that the water requirement of modified SDI will be lower than conventional SDI.
CHAPTER 4: DEVELOPING THE GLASSHOUSE APPARATUS

1. Introduction

It was proposed in the Review of Literature that an impervious layer beneath the drip line in sub surface drip irrigation could increase the upward flux of water, to replace water lost by soil evaporation or uptake by newly transplanted seedlings. It follows that, if the irrigation amount remains unchanged, then drainage will be reduced, and surface soil water content increased, by such a layer. It was further proposed that the rate of water movement would depend on soil physical properties and evaporative demand. A glasshouse experiment was designed to quantify the water balance components and effects on soil water content of placing an impermeable layer beneath the drip line. This Chapter describes the development and construction of the glasshouse apparatus.

Under field conditions, it is usual for soil to drain under gravity unless the soil profile is waterlogged (Hillel, 2004). So, whilst the soil water may be at zero suction at the point where water is applied, there will be a downward suction gradient (Prathapar and Qureshi, 1999; Hillel, 2004). The apparatus described here provided a hydraulic gradient in pots, in which the effects of SDI design could be quantified under controlled conditions. To provide this hydraulic gradient, a ‘tension table’ (Romano et al., 2002) connected to a ‘hanging water’ column was made in the bottom of each pot. This needed significant development work, which is described in this Chapter.

2. Experimental setup

The experimental apparatus consisted of a water inflow (irrigation) and outflow (drainage) system and hanging water column including burette. A tension table made of silica flour was used to maintain negative water potential at the bottom of each pot. The
‘Pots’ used were plastic boxes 50 x 35 x 30 cm, each containing 25 cm depth of soil above a tension table. The tension table was connected with tubing to hanging water column with a burette to indicate the suction in the tension table as the burette was raised or lowered. The tubing also served to collect drainage from the soil in the pot, as described below.

The irrigation setup had components of an irrigation main line, sub mains, connectors to each pot, and drip tape within each pot. The water pressure was maintained at 20 psi (138 kPa) using a pressure gauge in the main line.

In the experiments reported in Chapter 5, no plants were present. Irrigation amount was estimated from the duration of irrigation and the irrigation rate, which was measured under the controlled pressure of 138 kPa.

Thus evaporation from the Soil (E) was estimated as:

\[ E = I-D \]

Where I is the amount of irrigation water applied and D is the drainage water collected.

2.1. Selection of silica material

Silica ‘flour’ was used to create the tension table. There are different grades of silica flour available. Four generally available grades are 60, 80, 100 and 120. All four grades were tested in a Haines apparatus, also referred as a Buchner funnel (Haines, 1930), including a hanging water column. The objective was to choose a grade of silica which (i) remained saturated, and therefore held suctions, at up to about -100 kPa, and (ii) had high conductivity at this suction so that the tension table and soil above it responded quickly to changes in suction when the burette was raised or lowered.

Coarse silica (60G) was selected for the tension table. This porous material (silica 60G) was used to equilibrate the water in the soil sample. Using an external
supply of water (hanging water column) at the desired suction, equilibrium was attained in the tension table. The tension table also allowed drainage from the pot.

2.2. Hanging water column

The tension table was connected to a hanging water column which includes a long rubber tube attached to a burette. The soil was slowly wetted through the burette until the pot was saturated at the surface. Then the water level in the burette was lowered to give a suction of 60 cm which was maintained finally by lowering the level of the water in the burette. Excess water from the soil flowed out of the burette until equilibrium was reached at -60 cm (~5.9 kPa). After reaching equilibrium, any drainage following irrigation the excess water in the tension table was collected through the burette. The drainage from the drip tube was collected in a separate bottle.

2.3. Maintenance of experimental setup

The experimental setup was kept in a controlled environment in a glasshouse. In the system, the sub mains, the hanging water column tube and drainage pipe were black plastic pipes to avoid algal growth inside the pipe. The pots were covered by aluminium foil to prevent algal growth. The suction pipe of the hanging water column was checked daily and maintained without air.

3. Theory

To improve irrigation management under SDI, greater understanding of saturated and unsaturated hydraulic conductivity and upward flux or capillary rise of water is needed. Evaporation from soil depends on supply of energy and removal of vapour which together determine evaporative demand of the atmosphere and on continual supply of water (Hillel, 1972). Where a watertable occurs close to the soil surface, steady-state flow may take place from the saturated zone beneath, through the
unsaturated layer to the surface and thus evaporation continues without changing soil water content. The evaporation rate with a watertable present depends on soil properties and depth of watertable and it increases with increase in the suction at the soil surface (Gardner, 1958; Gardner and Fireman, 1958). When a shallow watertable is present, the external environmental conditions may influence evaporative demands (Hillel, 1972). So the relationship between water content and matric potential is important to understand water flow in soil (Noborio et al., 1999). In this research work, we are concerned about upward flux (evaporation from bare soil), soil water content and soil water potential.

Glasshouse apparatus under development. (Note: Tension table)
Glasshouse pot experiment. (Note: Soil moisture instruments)

Glasshouse apparatus – Hanging water column. (Note: Drainage collection)
CHAPTER 5: EFFECT OF MODIFIED SDI AND IRRIGATION FREQUENCY ON SOIL WATER AND COMPONENTS OF THE SOIL WATER BALANCE

1. Introduction

Efficient and environmentally sound irrigation requires management of the water balance. Drainage and runoff losses and soil evaporation must be minimized, and transpiration maximized. The type of irrigation system, and its management, can both affect each of these components of the water balance. A review of literature (Chapter 2) identified the soil water balance approach as one method to schedule or manage irrigation to minimize undesirable deep drainage and runoff, whilst satisfying crop water demand.

Subsurface drip (SDI) is a refinement in irrigation design that tries to reduce soil evaporation, leading to higher water use efficiency (Camp et al., 2000). Despite this and other advantages of SDI, crop establishment is often poor (Lamm, 2002) due to insufficient soil moisture to meet the demands of seedlings or seeds (Zimmer et al., 1988). In order to improve establishment with SDI, farmers may over-irrigate (Howell and Meron (2007) leading to increased drainage, or install the tape at shallow depth and water more frequently (Burt and Styles, 1994).

The field experiments (Chapter 3) showed that modified SDI (M.SDI) had higher surface soil water, more even water distribution and better crop establishment than conventional SDI (C.SDI) with the same irrigation amount and frequency. Even when only half the amount of irrigation water was applied to the M SDI (0.4 CF, spring experiment), crop establishment was as good as with C.SDI irrigated at the higher CF (0.8). The results with M.SDI imply greater upward flux and less downward flux of
water, although neither component of the water balance could be measured. Greater upward flux may increase soil evaporation, but it may also provide a more favourable soil moisture environment for establishing plants and lead to water savings.

Increased irrigation frequency in the field experiment had no effect on establishment, but it did result in wetter soil surfaces and improved seedling growth with both types of drip tape. In the spring experiment the response was greater with the modified tape (the interaction was significant). A response to irrigation frequency has been reported previously (Burt and Styles, 1994), but the interaction found in the field experiment suggests that irrigation frequency may need to be further increased to obtain the full benefit of the modification to the SDI. This important observation requires further work for confirmation.

Water flowing out from a buried emitter moves vertically and laterally to wet a volume of soil (Zur, 1996). Knowing the dynamics of water within the soil volume surrounding the emitter creates the opportunity to design improved irrigation systems as well as improve management of both water and chemicals (Zur, 1996). For a given soil, knowing the dynamics of water in the wetted volume can help to determine emitter spacing and the duration of irrigation. The shape and the dimensions of the wetting pattern around a buried source depend on the soil type as well as on the applied volume of water (Provenzano, 2007) and the frequency of application (Phene and Howell, 1984).

This glasshouse experiment quantified the components of the water balance under irrigation with conventional and modified sub-surface drip irrigation, and over a range of irrigation frequencies, in two soil types. The apparatus used (Chapter 4) enabled irrigation amount to be controlled, drainage to be quantified, and evaporation to be
calculated. The soil water content above the emitter and soil water potential near the soil surface were also measured.

The aim was to test the hypothesis that an impermeable layer under the drip tape reduces drainage and, given the same irrigation amount, increases the upward flux of water resulting in wetter surface soil and higher evaporation. A further aim was to assess the soil water response to irrigation frequency.

2. Materials and methods

2.1. Site

The experiment was conducted in a controlled temperature glasshouse at UWS, Hawkesbury Campus. The experiment was carried out without plants, so the only upward flux of water was by soil evaporation.

2.2. Experimental design

The treatments consisted of factorial combinations of two drip tape types and two soil types with two replicates arranges in a randomised complete block design. The two tape types were modified sub-surface drip (T$_1$) and conventional sub-surface drip (T$_2$). The two soil types were sand (S$_1$) and sandy loam (S$_2$). Each treatment was subjected to a sequence of different irrigation frequencies, one per two days; and one, two and four per day (I$_{0.5}$, I$_1$, I$_2$, I$_4$). There was insufficient glasshouse space to run the irrigation frequencies concurrently.

There were three phases of experiments. The first phase used a fixed irrigation rate (mm/day), which did not vary despite small variation in evaporation from day to day. The second phase used a fixed crop factor with varying irrigation rate, depending upon the previous day’s evaporation. Phases 1 and 2 were both under a low evaporative
demand. The third phase also used a fixed crop factor and varying irrigation rate, but with high evaporation.

2.3. The experimental apparatus

This is described in Chapter 4. Pots were 50x35x30 cm. Irrigation was applied via an automatic system capable of responding to small changes in evaporation.

2.4. Soil types

Soils were collected from two different locations on the UWS Hawkesbury campus. Soil particle size analysis was determined by the hydrometer method (Johnson and Stewart, 2004). Details are shown below (Table 18).

Table 18. Particle sizes of the sand and sandy loam soils

<table>
<thead>
<tr>
<th>Texture</th>
<th>Fraction</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Sandy soil</td>
<td>Sand</td>
<td>91.5</td>
</tr>
<tr>
<td></td>
<td>Silt</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>0.5</td>
</tr>
<tr>
<td>Sandy Loam soil</td>
<td>Sand</td>
<td>85.5</td>
</tr>
<tr>
<td></td>
<td>Silt</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>8.5</td>
</tr>
</tbody>
</table>

The soils were sieved and placed into the pots described in Chapter 4. After filling the pots with soil, they were brought to saturation by sub-soil watering, and then drained to -60 cm suction. Weed seeds were encouraged to germinate by sprinkling water for a few days before applying glyphosate (360g a.i./L).

2.5. Tape types

Two tape types (M.SDI and C.SDI) were compared. Both tape types were installed at 15 cm depth as they were in the field experiments. Drip tape emitters had 1.6 L h⁻¹ flow rate at 20 psi (138 kPa) pressure.
2.6. Irrigation rate and evaporation ($E_{\text{pan}}$) measurements

In Phase 1, irrigation rate was fixed at 5.3 mm/day (800 mL/pot/day), which was 0.8 of the pan evaporation of the previous four days in the glasshouse (6.0 mm/day). In Phases 2 and 3, the amount of water required for each irrigation was calculated by multiplying a ‘crop factor’ by the previous day’s pan evaporation in the glasshouse, or over the previous two days with the $I_{0.5}$ treatment. The crop factor of 0.8 chosen for Phase 1 was the crop factor used in field experiment 2, following the recommendation of Howell and Meron (2007) that a high crop factor be used for crop establishment using seedling transplants, even if transpiration is low. Having assessed the results of Phase 1 and the field experiments, Phases 2 and 3 used a crop factor of 0.4.

Evaporation in the glasshouse was measured by using a single pan equal in size to the treatment pots. It was an identical tub to that used in the pots, with the walls covered in aluminium foil. Depth of evaporation was measured daily with a ruler, the volume of evaporation calculated, and then replaced. The phases of the experiment were carried out under a ‘low’ (Phases 1 and 2) or ‘high’ (Phase 3) evaporative demand achieved by varying temperature from 25°C to 35°C (with diurnal variation of 5°C).

Maximum/minimum and wet /dry bulb thermometers were used to measure temperature and relative humidity daily.

2.7. Soil water measurements

*Theta probe*: Volumetric soil water content was measured by a single Theta probe (model of ML-2x a Delta T-Device from Measurements Engineering Australia) inserted vertically in each pot. The sensor probes were located to read at 5-10 cm depth, 10 cm away from the drip tape. The probes were connected to a data logger (Data logger Tbug, Measurement Engineering Australia) programmed to take measurements at 15 min. intervals, which were generally before irrigation, at the time of irrigation and after
irrigation. Data presented are for the reading following irrigation, when drainage had ceased. The results are given as percentage (%).

**Gypsum blocks:** Soil water potential near the soil surface was measured daily, following irrigation and when drainage had ceased, by using gypsum blocks (GB Light, Measurement Engineering Australia) and expressed as kPa. The GB Light is used in all soil types and has a range from 0 to 200 kPa. The sensors were connected to GBug data logger (MEA), which was programmed to take readings at two-hour intervals. The blocks were placed in all treatments horizontally at 3-5 cm depth and 10 cm away from drip tape.

**Tensiometer:** These also measure soil water potential (kPa), but over a narrower range but with greater precision than the gypsum blocks. They were used in slightly deeper soil where only small variations in potential were expected. They were installed with the ceramic cup at 5-10 cm depth, above the drip line and 10 cm away from the emitter. Data were recorded when drainage had ceased.

### 2.8. Water balance components

Drainage was measured daily. Water was collected after irrigation when no further drainage occurred (up to 3 hrs) and weighed. Since the irrigation amount was known and there was no runoff, soil evaporation could be determined simply from the water balance equation:

\[ E_s = I - D \]

Calculation of \( E_s \) assumed steady-state soil water content on a day-to-day basis. That is, water moved from the irrigation input to the atmosphere without contributing to changes in soil water. This is an approximation to steady state as soil water content must vary diurnally. Daily drainage and soil evaporation were observed until they
approached an apparent ‘steady state’. Data for the last 3 days were averaged to provide estimates for D and $E_s$ pertaining to any treatment or phase, and subsequently analysed.

2.9. Statistical analysis

Analysis of variance (ANOVA) was conducted on data using MiniTab ver. 15 statistical program. An ANOVA on soil water and drainage data was undertaken for each irrigation frequency within each evaporative demand (Phase). The estimates of soil evaporation were analysed by linear regression to examine the effect of irrigation frequency.

3. Results

3.1. Pan evaporation in the glasshouse

Figure 7 a, b, c shows the moving average for evaporation in all treatments. Evaporation in last few days of each ‘run’ coincides with estimates of soil evaporation or drainage at approximate ‘steady state’.

![Pan evaporation graphs]

**Fig. 7a. Pan evaporation in Phase 1 (mm/day)**
In the last three days, evaporation was highest in the 1/day and lowest in 4/day treatments.

Fig. 7b. Pan evaporation Phase 2 (mm/day)
Evaporation tended to be lower in the 1/day and higher in the 2/day treatments.

Fig. 7c. Pan evaporation in Phase 3 (mm/day)
3.2. Drainage

In all three phases of the experiment, the mean drainage at ‘steady state’ for the modified SDI was less than for conventional SDI. Soil types generally did not show significant differences. The detailed results follow.

**Phase 1**

In this phase of the experiment, drainage from the different irrigation frequency treatments was compared with equal application of irrigation water to all treatments on every day. Within each irrigation frequency, the modified SDI gave significantly less drainage than in the conventional SDI treatment (Table 19). Within irrigation frequency, the effects of soil type and its interaction with tape type were not significant (p>0.05). Over all irrigation frequencies, drainage was 20% less in the modified SDI (from Table 19). Higher irrigation frequency (four/day) in the modified SDI resulted in least drainage (194 mL/pot/day). Less frequently irrigated treatments overall resulted in the highest drainage, but the statistical significance of this difference could not be tested.

**Table 19. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 1) at steady state**

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand M.SDI</th>
<th>C.SDI</th>
<th>S.Loam M.SDI</th>
<th>C.SDI</th>
<th>Mean M.SDI</th>
<th>Mean C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One/2 days</td>
<td>257</td>
<td>326</td>
<td>279</td>
<td>330</td>
<td>268</td>
<td>328</td>
</tr>
<tr>
<td>One/day</td>
<td>251</td>
<td>323</td>
<td>226</td>
<td>328</td>
<td>239</td>
<td>326</td>
</tr>
<tr>
<td>Two/day</td>
<td>269</td>
<td>318</td>
<td>272</td>
<td>322</td>
<td>270</td>
<td>320</td>
</tr>
<tr>
<td>Four/day</td>
<td>194</td>
<td>256</td>
<td>193</td>
<td>248</td>
<td>194</td>
<td>252</td>
</tr>
</tbody>
</table>

**, *** Significant p<0.01, 0.001 respectively (Each frequency analysed as a single experiment)**

**Phase 2**

In this phase, irrigation amount varied according to daily pan evaporation, in contrast to Phase 1 in which irrigation amounts were fixed. Despite the change in irrigation scheduling strategy, the modified SDI again had significantly less drainage than conventional SDI within any of the irrigation frequencies. Overall, drainage was
29% less in the modified SDI than in conventional SDI (calculated from Table 20).

Once again, drainage was least with the high irrigation frequency.

Table 20. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 2) at steady state

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th>S. Loam</th>
<th>Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One/2 days</td>
<td>365</td>
<td>456</td>
<td>352</td>
<td>455</td>
</tr>
<tr>
<td>One/day</td>
<td>122</td>
<td>168</td>
<td>116</td>
<td>161</td>
</tr>
<tr>
<td>Two/day</td>
<td>116</td>
<td>153</td>
<td>112</td>
<td>154</td>
</tr>
<tr>
<td>Four/day</td>
<td>196</td>
<td>333</td>
<td>203</td>
<td>342</td>
</tr>
</tbody>
</table>

***, ** Significant at p<0.01, 0.001 respectively (Each frequency analysed as a single experiment)

**Phase 3**

Drainage was again significantly less in the modified SDI than the conventional SDI at all irrigation frequencies. Averaged over all irrigation frequencies, drainage was 32% less under modified SDI than with the conventional SDI (from Table 21). Least drainage (230 mL/pot/day) was obtained in the modified SDI with frequent irrigation (four/day). Again, high irrigation frequency substantially reduced drainage.

Table 21. The effects of tape type, irrigation frequency and soil type on drainage (mL/pot/day) (Phase 3) at steady state

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th>S. Loam</th>
<th>Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One/2 days</td>
<td>318</td>
<td>445</td>
<td>315</td>
<td>434</td>
</tr>
<tr>
<td>One/day</td>
<td>278</td>
<td>453</td>
<td>261</td>
<td>454</td>
</tr>
<tr>
<td>Two/day</td>
<td>372</td>
<td>490</td>
<td>370</td>
<td>489</td>
</tr>
<tr>
<td>Four/day</td>
<td>233</td>
<td>350</td>
<td>227</td>
<td>348</td>
</tr>
</tbody>
</table>

*** Significant at p<0.001(Each frequency analysed as a single experiment)
3.3. Evaporation from bare soil

The results are shown in Table 22 for all phases of the experiment, together with the irrigation and drainage data from which they were derived. All data are reported as mm/day, after dividing the volumetric data by the surface area of the pot. As there was no apparent effect of soil type on drainage, soil evaporation is the pooled data for soil types.

Table 22. Water balance components at ‘steady-state’ for the three phases of the glasshouse experiment: pan evaporation \((E_{\text{pan}})\), irrigation \((I)\), drainage \((D)\) and soil evaporation (averaged over replicates and soil types)

<table>
<thead>
<tr>
<th>Irr./day</th>
<th>Av. (E_{\text{pan}}) (mm/d)</th>
<th>Av. I (mm/d)</th>
<th>Av. D (mm/d)</th>
<th>Av. (E_{\text{soil}}) (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>Phase 1</td>
<td>0.5</td>
<td>3.0</td>
<td>4.6</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4.7</td>
<td>4.6</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.2</td>
<td>4.6</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.0</td>
<td>4.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Phase 2</td>
<td>0.5</td>
<td>2.7</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.0</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.3</td>
<td>1.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.7</td>
<td>2.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Phase 3</td>
<td>0.5</td>
<td>7.0</td>
<td>4.0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>8.0</td>
<td>4.6</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.0</td>
<td>5.2</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.7</td>
<td>5.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Because irrigation amount is constant across treatments for any given period, the calculated \(E_{\text{soil}}\) values must be the inverse of drainage. Evaporation was thus always higher for the M.SDI than C.SDI. It also tended to be higher at the higher irrigation frequencies. The response to irrigation frequency is shown in Fig. 8. In each phase of the experiment, \(E_{\text{soil}}\) increased with irrigation frequency. All of the regressions were statistically significant. Whilst soil evaporation from both tape types responded to increasing frequency, it is notable that within any Phase, the greatest upward flux from C.SDI (at four irrigations/day) was no higher than with the M.SDI with two or fewer irrigations per day.
Effect of irrigation frequency on soil evaporation in M.SDI (Phase 1)

\[ y = 0.1235x + 2.9435 \]

\[ R^2 = 0.6543 \]

Effect of irrigation frequency on soil evaporation in C.SDI (Phase 1)

\[ y = 0.1183x + 2.5783 \]

\[ R^2 = 0.8377 \]

Effect of irrigation frequency on soil evaporation in M.SDI (Phase 2)

\[ y = 0.3252x + 0.3652 \]

\[ R^2 = 0.9187 \]

Effect of irrigation frequency on soil evaporation in C.SDI (Phase 2)

\[ y = 0.1757x + 0.1957 \]

\[ R^2 = 0.829 \]

Effect of irrigation frequency on soil evaporation in M.SDI (Phase 3)

\[ y = 0.3617x + 2.3217 \]

\[ R^2 = 0.825 \]

Effect of irrigation frequency on soil evaporation in C.SDI (Phase 3)

\[ y = 0.4174x + 1.4174 \]

\[ R^2 = 0.9207 \]

Fig. 8. Effects of tape types and irrigation frequencies on mean soil evaporation (mm) from bare soil at ‘steady state’

3.4. Volumetric soil water content

The soil water content was measured after irrigation at 10 cm above and 10 cm to the side of the emitter. The data reported in Tables 23-25 were measured after irrigation, for all three phases of the experiment.

The modified SDI generally had higher soil moisture content than conventional SDI, although the difference was not always significant, and there were exceptions in Phase 1. The most consistent response was an increase in water content with modified SDI at the highest irrigation frequency, where the difference between tape types was
always significant. There was no significant effect of soil type. The detailed results are presented below.

**Phase 1**

The soil water content averaged over soil types was significantly higher (p<0.05) with modified SDI (31%) than with conventional SDI (27%) but only with frequent irrigation (four/day). At lower irrigation frequencies, the trend was for the modified SDI to have lower water content than conventional SDI, but the differences were not significant. Soil type did not show any significant difference between the irrigation frequencies.

**Table 23. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 1) at steady state**

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand M.SDI</th>
<th>Sand C.SDI</th>
<th>S. Loam M.SDI</th>
<th>S. Loam C.SDI</th>
<th>Mean M.SDI</th>
<th>Mean C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One/2 days</td>
<td>28.8</td>
<td>31.5</td>
<td>27.3</td>
<td>26.7</td>
<td>28.1</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>One/day</td>
<td>25.1</td>
<td>30.8</td>
<td>27.2</td>
<td>27.3</td>
<td>26.1</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Two/day</td>
<td>26.2</td>
<td>30.2</td>
<td>29.7</td>
<td>24.3</td>
<td>27.9</td>
<td>27.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Four/day</td>
<td>31.9</td>
<td>27.8</td>
<td>30.3</td>
<td>25.9</td>
<td>31.1</td>
<td>26.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

* Significant at p<0.05, NS-Not Significant (Each frequency analysed as a single experiment)

**Phase 2**

The soil water content was consistently higher in the modified SDI compared with the conventional SDI, but the differences were statistically significant only with the most frequent irrigation (Table 24). Again, soil type did not show any significant difference in the soil water content.

**Phase 3**

Soil water content was again higher in the modified SDI than the conventional SDI in all irrigation frequencies (Table 25). The difference was statistically significant (p<0.05) in the once/two days and four times daily treatments.
Table 24. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 2) at steady state

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th>S. Loam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One/2 days</td>
<td>27.4</td>
<td>30.2</td>
</tr>
<tr>
<td>One/day</td>
<td>29.2</td>
<td>28.9</td>
</tr>
<tr>
<td>Two/day</td>
<td>28.1</td>
<td>28.8</td>
</tr>
<tr>
<td>Four/day</td>
<td>29.7</td>
<td>30.6</td>
</tr>
</tbody>
</table>

* Significant at p<0.05, NS-Not Significant (Each frequency analysed as a single experiment)

Table 25. The effects of tape type, irrigation frequency and soil type on soil water content (%) (Phase 3) at steady state

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th>S. Loam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One/2 days</td>
<td>26.2</td>
<td>30.9</td>
</tr>
<tr>
<td>One/day</td>
<td>27.4</td>
<td>29.3</td>
</tr>
<tr>
<td>Two/day</td>
<td>27.1</td>
<td>33.9</td>
</tr>
<tr>
<td>Four/day</td>
<td>27.5</td>
<td>34.1</td>
</tr>
</tbody>
</table>

* Significant at p<0.05, NS-Not Significant (Each frequency analysed as a single experiment)

3.5. Soil water potential at 3-5 cm depth

This was measured daily, following irrigation, using gypsum blocks (Tables 26-28). This near-surface measurement is the depth of transplanting for lettuce.

Phase 1

Responses in water potential to tape type were small but broadly mirrored those for volumetric water content. The effect of tape type was significant (p<0.01) in the high irrigation frequency (Table 26). Wetter surface soil (-7 kPa) was obtained in the modified SDI with four irrigations per day, compared with the conventional SDI (-9 kPa). The interaction between soil type and tape type was also significant (p<0.01) in the high irrigation frequency. As irrigation frequency decreased, the soil near the
surface became drier in both tape types, and the effect of tape type was also not
significant.

**Table 26. The effects of tape type, irrigation frequency and soil type on soil water
potential (-kPa) (Phase 1) at steady state (3-5 cm depth)**

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th></th>
<th>S.Loam</th>
<th></th>
<th>Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One/2 days</td>
<td>14</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>One/day</td>
<td>13</td>
<td>13</td>
<td>9</td>
<td>12</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Two/day</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Four/day</td>
<td>7</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

** Significant at p<0.01, NS-Not significant (Each frequency analysed as a single experiment)

**Phase 2**

Significant (p<0.01) but contrasting responses were found between tape types
(Table 27). In the treatment with four irrigations per day, modified SDI soil was wetter,
whereas the converse was true with one irrigation/day.

**Table 27. The effects of tape type, irrigation frequency and soil type on soil water
potential (-kPa) (Phase 2) at steady state (3-5 cm depth)**

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th></th>
<th>S.Loam</th>
<th></th>
<th>Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One/2 days</td>
<td>8</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>One/day</td>
<td>15</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Two/day</td>
<td>12</td>
<td>11</td>
<td>12</td>
<td>11</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Four/day</td>
<td>8</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>11</td>
</tr>
</tbody>
</table>

** Significant at p<0.01, NS-Not significant (Each frequency analysed as a single experiment)

**Phase 3**

 Soil was slightly wetter in the modified SDI compared with conventional SDI in
all irrigation frequencies, but the tape difference was significant only with high
irrigation frequency (four/day) (Table 28). The effect of soil types was not significant.
3.6. Soil water potential at 5-10 cm depth

The soil water potential at 5-10 cm depth measured with a tensiometer was less negative (higher soil moisture) with the modified SDI (Tables 29-31). The response was more consistent than with the other two measures of soil water, with no cases of conventional SDI being wetter than the modified SDI, and more of the differences being statistically significant.

Table 29. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 1) at steady state (5-10 cm depth)

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand</th>
<th>S.Loam</th>
<th>Mean</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M.SDI</td>
<td>C.SDI</td>
<td>M.SDI</td>
<td>C.SDI</td>
</tr>
<tr>
<td>One/2 days</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>One/day</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two/day</td>
<td>8</td>
<td>11</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four/day</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*, ** Significant at p<0.05, 0.01, NS –Not significant (Each frequency analysed as a single experiment)

The effect of soil type on water potential was not significant (p≥0.05). There was a trend for the soil to be wetter with the more frequent irrigation, but this could not be tested statistically.
Table 30. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 2) at steady state (5-10 cm depth)

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand M.SDI</th>
<th>C.SDI</th>
<th>S.Loam M.SDI</th>
<th>C.SDI</th>
<th>Mean M.SDI</th>
<th>Mean C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One/2 days</td>
<td>7</td>
<td>9</td>
<td>7</td>
<td>9</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>One/day</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>*</td>
</tr>
<tr>
<td>Two/day</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Four/day</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

* Significant at p<0.05, NS- Not Significant (Each frequency analysed as a single experiment)

Table 31. The effects of tape type, irrigation frequency and soil type on soil water potential (-kPa) (Phase 3) at steady state (5-10 cm depth)

<table>
<thead>
<tr>
<th>I.F. (Irri./day)</th>
<th>Sand M.SDI</th>
<th>C.SDI</th>
<th>S.Loam M.SDI</th>
<th>C.SDI</th>
<th>Mean M.SDI</th>
<th>Mean C.SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>One/2 days</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>One/day</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Two/day</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Four/day</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

* Significant at p<0.05, NS- Not Significant (Each frequency analysed as a single experiment)

4. Discussion

The results of this experiment reveal the potential for the modified SDI to increase water-use efficiency and improve plant establishment, thus confirming the results of the field experiments (Chapter 3). The greater upward flux of water, that is the calculated soil evaporation, was sufficient to keep the soil wetter whilst at the same time reducing drainage. The improved soil moisture is expected to improve crop growth during establishment, even in sandy soils with frequent irrigation (daily) under vegetable production (Dukes and Scholberg, 2005).
4.1. Drainage and soil evaporation

Reducing drainage can improve irrigation efficiency and improve the uniformity of applied water (Hanson, 1987). It should also help to reduce over-irrigation (TANJI and Hanson, 1990; Jensen et al., 1990) and the associated environmental risks.

The modified SDI resulted in lower drainage than the conventional SDI with all irrigation frequencies under different evaporative demands, and with different irrigation rates. The average reduction was 20, 29, and 32% in the three Phases, a mean reduction in drainage of 27%. It appears that the reductions in drainage are greatest when evaporative demand is greatest, reflecting higher soil evaporation under these conditions.

The results demonstrate that irrigation system design has the potential to manage drainage below the root zone in the way proposed for subsurface drip by Phene et al. (1991), Darusman et al. (1997), and Ayars et al. (1999). More importantly, it shows specifically that modifying the drip tape to include an impermeable layer beneath the tape substantially reduces the drainage found even with conventional SDI.

This is a useful finding, as the unambiguous results from the controlled conditions of this experiment provide support for field experience where drainage is hard to quantify but sometimes assumed.

One assumption sometimes made is that high frequency SDI in particular has the potential to reduce drainage (Ayars et al., 1999), particularly on sandy soil (Howell et al., 1995). Whilst the data for irrigation frequency could not be combined into a single ANOVA for statistical reasons, there was a large consistent response across tape types (M.SDI and C.SDI), soil types and evaporative conditions (Phases) that collectively support the argument that increased frequency reduces drainage under SDI. The reduction in drainage with increased irrigation frequency was of the same order as the response to tape type.
The relationship between drainage and evaporation has been well documented under subsurface drip irrigation in the field. Generally, for a given input of water, if soil evaporation (or ET) is reduced then drainage must increase (Darusman, et al., 1997). With the controlled conditions of the glasshouse experiment, it was possible to quantify the split between drainage and \( E_s \) and its responses to drip type, irrigation frequency or environmental condition. Significantly, increasing irrigation frequency increased soil evaporation (Fig. 8). Over all soil types, tape types and Phases, the increase in frequency from once every second day to four times daily approximately double the amount of water evaporated. This water is available for either \( E_s \) or transpiration, when plants are present.

As others have shown, high irrigation frequency maintained relatively high evaporation rates and kept the soil surface wet (Meshkat et al., 2000).

### 4.2. Soil water

Many authors have emphasized the importance of maintaining relatively constant soil water potential in the range favouring plant growth (Phene and Howell, 1984; Pogue and Pooley, 1985; Phene et al., 1989; Thompson et al., 2004). This is especially important for crop establishment under SDI (Plaut et al., 1985).

Modified SDI generally had the highest soil moisture content and highest water potential (least negative). The only exception was in Phase 1, at low irrigation frequency, when the conventional SDI had higher soil moisture than the modified SDI. This discrepancy can be accounted for by tunnelling seen in the conventional SDI pots. However, in the modified SDI the modification plays an important role to avoid tunnelling (Miller et al., 2000).

The volumetric soil water content and water potential generally increased with irrigation frequency, but this trend could not be tested statistically. It suggests at least that high frequency irrigation maintains higher soil water content, whether under SDI or
modified SDI, as others have found (El-Gindy and El-Araby, 1996; Silber et al., 2003; Segal et al., 2006; Provenzano, 2007; Ismail et al., 2008).

There was also strong indication that the modified SDI combined with high irrigation frequency led to highest water content and least negative potential in the top soil. In every set of soil water data, that is three methods of measuring soil water in three experiment Phases, M.SDI combined with high irrigation frequency had the highest water content.

The soil water response is best illustrated by the volumetric soil water data in Table 23-25. In these data, the highest water content in C.SDI, under high-frequency irrigation, was approximately the same as in the M.SDI with low frequency irrigation. This result parallels the soil evaporation data, in that greatest upward flux of water seems to be associated with highest soil water content. It also supports the field experiments. That is, whilst soil water content responded to irrigation frequency with both types of tape, the soil was always wetter with the modified tape. In the field experiment, high frequency irrigation coupled with the modified tape type improved soil moisture and plant fresh weight (Chapter 3).

This glasshouse experiment was carried out to develop an understanding of soil physics and irrigation. This knowledge was connected with an understanding of how much water (irrigation amount) to apply to re-wet the soil, including understanding of the components of the water balance. This concept was reviewed by Grimes et al. (1990); Or and Coelho (1996) and Hanson et al. (2008).

The barrier under the drip line led to higher water content and potential in the soil above the barrier, and the drainage or downward flux of water was decreased (Kirkham and Horton, 1990; Kiuchi et al., 1994).
The KISSSTM product should enable crops to be established with less risk than conventional SDI, without the need for excessive irrigation during establishment. But this may require increased irrigation frequency.

The findings suggest that irrigation frequency needs to be adjusted as crops develop. Whilst high upward flux is essential for good establishment, it is undesirable for established plants with a low leaf area index. This is because the high upward flux will contribute to wasteful soil evaporation.

5. Summary of the results

In this glasshouse study the two subsurface drip tape types were compared in two soil types, under a range of irrigation frequencies and environmental regimes. Generally, the average soil water content above the emitter under approximate steady state was improved with the modified SDI. Frequent irrigation also appeared to increase surface soil water, especially with the modified SDI. The results of the experiments indicate that the drainage was less under the modified SDI than the conventional SDI and with more frequent irrigation. In other words, the soil evaporation was more in the modified SDI due to improved upward movement of water.

The modified SDI (KISSSTM) with frequent irrigation appears to be suitable for the coarse textured soils. The product should enable crops to be established with less risk than conventional SDI, without the need for excessive irrigation before or during establishment.
CHAPTER 6: GENERAL DISCUSSION AND CONCLUSIONS

1. Introduction

Current management of irrigation water in the peri-urban vegetable industry is largely based on surface irrigation, most commonly with overhead sprinklers. Water use efficiency is low and environmental impacts are high (Cornish et al., 2005). Subsurface drip irrigation has great potential in this situation (eg Chase, 1985; Qassim, 2003), but problems of ‘tunnelling’, variable soil surface water and risky crop establishment need to be addressed (Mizyed and Kruse, 1989; Lamont et al., 2002; Qassim, 2003; Lamm and Camp, 2007). It has been said that despite many successes with SDI (Schwankl et al., 1990; Lamm and Trooien, 2005; Roberts et al., 2008), germination/establishment remains the major challenge with SDI (Raine and Foley, 2001), and that possibly crops cannot be established at all this way (Harris, 2005a, b), meaning that conjunctive irrigation from another source is required along with SDI.

To overcome these problems with SDI, researchers have investigated shallow tape installation and increased irrigation frequency (Burt and Styles, 1994; Vazquez et al., 2006); and modification to the SDI design (Welsh et al., 1995; Charlesworth and Muirhead, 2003). None of these approaches has been completely successful, although the wetting pattern of SDI has been influenced by placing a continuous impermeable membrane beneath the drip line, with the aim of inhibiting the downward flux of water from the emitters and providing a broad moisture front rather than a point source (Miller et al., 2000). In Chapter 2, it was hypothesised that this membrane would create a small temporary watertable from which the upward flux of water would be greater than in conventional SDI and the drainage less. This hypothesis underpinned the research in this thesis that sought to evaluate a newly-developed SDI which included an impermeable membrane and geotextile (KISSSTM).
The research questions were:

1. Does an impermeable layer beneath the drip tape (modified SDI) improve surface soil water conditions and crop establishment, compared with conventional SDI?

2. Does the modified SDI offer any advantage over using conventional SDI with greater irrigation amount or frequency?

A further objective was to determine if irrigation management (amount and frequency) with SDI should take account of soil type and evaporative demand.

2. Industry context

The literature review considered vegetable industry issues related to irrigation, with an emphasis on SDI and the production and irrigation management of lettuce. It was noted that peri-urban vegetable production is expanding in Australia (Johnson et al., 1998) and globally (Brook and Davila, 2000), and that there is growing competition for water between vegetable growers and the urban community. The review highlighted increased consumer demand for vegetables in local markets (Hickey et al., 2006). Rapid growth in the Sydney Basin is associated with an influx of new farmers and a lack of knowledge of irrigation scheduling and management, which is linked to low irrigation efficiency and high environmental impact (Cornish et al., 2005).

Adoption of more efficient systems such as drip irrigation has been low, partly because of a lack of knowledge about adapting systems to the varied soils of the region (Cornish et al., 2005) and the wide range of evaporative demands between cooler and warmer months (Badgery-Parker, 1999). The need to replace drip tape after every crop and the likely need for an alternative source of irrigation for establishment are major economic disincentives (Christen et al., 2006). However, with the adoption of reduced tillage and semi-permanent beds for vegetables (Senn and Cornish, 2000), there is an
opportunity to introduce subsurface drip irrigation with its many advantages, including longer life than surface drip.

It was concluded that SDI would be a good option for the vegetable industry, provided the risks of poor plant establishment could be overcome. The industry mainly uses seedling ‘transplants’ for plant establishment (Dimsey and Vujovic, 2005), so ‘establishment’ in the research reported here refers to the survival and early growth of the transplanted seedlings. The research used lettuce, which is the major crop of the Sydney Basin (Tony, 2004).

Past research has shown that the major disadvantage of SDI is the risk of poor establishment (Zimmer et al., 1988; Deery, 2003). So the evaluation of the modified SDI (KISSSTM), focussed on its effects on surface soil water and seedling survival and early growth. Consideration was also given to reducing the drainage, which may be associated with over-watering, which is recommended for good establishment with conventional SDI (Hanson et al., 1994).

3. Findings from the research

3.1. Evaluation of modified SDI

Soil water, crop establishment and early growth

The modification in the subsurface drip tape improved soil water near the soil surface in both field experiments, where pan evaporation ranged between 2 mm/day (autumn) and 6 mm/day (spring), and in two soil types in the glasshouse, where pan evaporation ranged between 2 and 10 mm/day. Soil in the M.SDI was consistently wetter than with the C.SDI at comparable irrigation frequencies and crop factors (irrigation amounts). So the potential advantages of this innovation should be expressed over a range of conditions. In the field, soil water content was also more uniform in the M.SDI treatment.
The improved surface soil water regime was associated with improved lettuce crop establishment, and higher leaf appearance rate, leaf size (leaf width and length) and fresh weight. Differences in fresh weight were substantial. The modified SDI system recorded average increases over the conventional SDI of 16% and 25% in the autumn and spring experiments, respectively. If these differences in plant weight continue through to harvest, a reasonable expectation with crops such as lettuce, then the modification to the SDI will result in greater irrigation efficiency (yield per unit of irrigation) to mirror the plant weight response. Management of irrigation with the modified SDI to optimise efficiency is discussed in Section 3.2. Plant weight was also more uniform with the modified SDI than with conventional SDI, offering practical advantages to the farmer at harvest time (Schwankl et al., 1993).

**Fig. 9. Plant fresh weight response to volumetric soil water content, both seasons**

The critical importance of surface soil water for establishment is demonstrated by the relationship between soil water content and plant weight at the end of the establishment period in the field experiments (Figs. 9 and 10). In both experiments there was a close relationship between plant weight and soil water, regardless of the source of variation in soil water: tape type, crop factor, or irrigation frequency (Fig. 9) or position in the bed (Fig. 10).
Fig. 10. Fresh weight response to variation in volumetric soil water within the bed, spring 2007

In previous work with a modified SDI, the soil was wet more uniformly (Miller et al., 2000). The modified drip tape product has undergone extensive development since then, especially in dimensions, and is now sold under a new trade name. This presumably explains why the modified SDI performed better in the present research compared with earlier research (Charlesworth and Muirhead, 2003). In addition, Charlesworth and Muirhead (2003) noted that the Handwood loam soil in their research had good hydraulic properties, which resulted in good crop establishment in C.SDI despite it being drier. Also, they studied seed germination rather than establishment of seedling transplants which may have less critical moisture requirements.

**Drainage**

Drainage could not be measured in the field experiment, but the finding that the soil surface was wetter than in conventional SDI, given the same amount of irrigation, suggested that the upward flux was greater and the drainage should be less with the modified SDI. Thus the gain in irrigation efficiency, noted above, arises because more water is transpired (as well as evaporated), and less is drained. Reduced drainage has important environmental implications (Hollinger et al., 2001).

The glasshouse experiment provided direct evidence that drainage is reduced in the modified SDI system given the same irrigation and environmental conditions. This
was observed regardless of soil type, and in all irrigation frequencies, and under different evaporative demands. Whilst the drainage component of the water balance was significantly reduced, soil evaporation was greater in the modified SDI. Increased soil evaporation is not in itself an indicator of improved irrigation efficiency, but it is important because it means that more of the irrigation water was potentially available for use by establishing seedlings.

Because of poor establishment with conventional SDI, excessive water is often used in an attempt to achieve the near saturation required for germination and establishment (Vazquez et al., 2005). It is not uncommon to find deep drainage losses during the first few irrigations of the season where SDI systems are used to germinate seeds (Patel and Rajput, 2007). The present results indicate that the modified SDI evaluated here has the potential to achieve significantly better establishment whilst also reducing drainage losses.

3.2. Irrigation management: amount and frequency

An objective of this research was to determine if irrigation management with SDI should be varied according to soil type and evaporative demand. From the review of literature, it was concluded that the adequacy of the water supply from SDI to the newly transplanted seedling would be a function of (amongst other factors) soil hydraulic conductivity (soil type) and evaporative demand (Zimmer et al., 1988; Charlesworth and Muirhead, 2003). Also, the underlying hypothesis was that the impermeable layer beneath the drip tube would create a temporary watertable, and the upward flux of water from a watertable will be greater than from unsaturated soil, which is free to drain during and after irrigation (Hillel, 1972). So soil and crop responses to irrigation amount and frequency with modified SDI might be different from earlier studies of these management variables with conventional SDI. Management factors include the amount of irrigation, which is varied according to crop factor (CF), and the
irrigation frequency (IF). Both of these were included as treatments in the field experiment, whilst the glasshouse work focused on irrigation frequency.

In the field experiments, soil water content and plant weight responded to increased crop factor (CF), that is increased irrigation amount, and to increased irrigation frequency (IF). This was so for both the modified SDI and the conventional SDI, the latter being in broad agreement with other studies in light textured soil (Ayars et al., 1999) and particularly on sandy soil (Ghali and Svehlik, 1988; Howell et al., 1997).

For every combination of CF and IF, the growth of plants with the modified SDI was greater than with conventional SDI. Importantly, at high irrigation frequency (4/day), plant weight with the modified SDI treatment was 10% greater than with conventional SDI, even when given half the amount of irrigation (CF 0.4 versus 0.8). When given an equal amount of water (CF 0.8) with frequent irrigation (4/day), the modified SDI resulted in crop fresh weights that were 35% greater than in conventional SDI. This translates directly into improved irrigation efficiency at this stage of the crop. Thus, although the modified SDI with high irrigation frequency had distinct advantages over conventional SDI, including similar seedling growth with half the water, it may still be necessary to have a high crop factor as well as frequent irrigation to get the best results.

Results from under controlled conditions in the glasshouse confirmed that the upward flux of water to meet the evaporative demand was greater in the modified SDI. They also confirmed that the upward flux was greater with more frequent irrigation. Soil water content and potential were also higher with more frequent irrigation. It is evident with findings of Haman and Smajstrla (2002). Over both field and glasshouse experiments, the effect of irrigation frequency was quite consistent, regardless of soil type and evaporative demand, and there was little evidence of an interaction between
these variables and tape type. So, despite the predictions from theory that these factors would interact with irrigation management and tape type, in practice the effects were too small to be detected. However, under a wider range of soil types, or under more severe evaporative conditions, differences may emerge. Further research is required to establish the optimum irrigation regime for different soil types and evaporative regimes when using the modified SDI.

The response to frequent irrigation with the modified SDI is in line with the theory that a temporary water table is available for a short period after irrigation, above the impermeable layer. The period is short because the volume of water held is small\(^6\). More frequent irrigation creates this temporary watertable more often than less frequent irrigation. It is likely that in higher evaporative demand this temporary reservoir of water is depleted more quickly, necessitating more frequent irrigation. The modified SDI is different from the conventional SDI in that a small amount of water is held against drainage and at zero potential, which allows for a higher rate of upward flux (Gardner, 1958).

Frequent water application through SDI has improved water use efficiency in other research with vegetables, as reported by El-Gindy and El-Araby (1996) and Silber et al. (2003). These studies suggest that for shallow rooted vegetable crops establishment can be obtained with more frequent irrigations, particularly on sandy soil (Dukes and Scholberg, 2005). From these studies, and the present work, it appears that Harris (2005a) was unduly pessimistic in considering that establishment could not be achieved with SDI.

The present results agree with the earlier findings on ‘pulse irrigation’ (Miller et al., 2000), but they also show that, with a modified SDI, either fewer pulses, or less

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\(^6\) If we assume each emitter supplies, a tube 10 cm wide, 50 cm long, to a depth of 3 mm, the volume of water held per irrigation would be 150 cm\(^3\). The water requirement in the glasshouse experiment under high evaporation was ~ 800mL/day, to be supplied by a single emitter.
irrigation water, may be used to achieve a similar result. Or, in some conditions, even better results may be achieved with a combination of pulse irrigation and a relatively high crop factor.

There were further benefits to be had from increasing irrigation frequency. In the conventional SDI, higher irrigation frequency reduced the severity of tunnelling.

The combined field and glasshouse results show that the KISSSTM product should enable crops to be established with less risk than conventional SDI, without the need for excessive irrigation during establishment. However, this may require increased irrigation frequency.

The findings also show that irrigation frequency needs to be adjusted as crops develop. Whilst high upward flux is essential for good establishment, it is undesirable for established plants with a low leaf area index. This is because the high upward flux will contribute to wasteful soil evaporation.

4. Future research

4.1. Water saving using modified SDI

Whilst this research showed that the modified SDI improves seedling survival and crop growth during the establishment period, the main focus of the work, it also suggested that irrigation efficiency may be improved. Comparisons with existing sprinkler irrigation and other systems are now required for the duration of the crop to quantify the differences in irrigation efficiency and environmental performance.

Irrigation management to optimise crop production, irrigation efficiency and runoff/drainage will be different from irrigation for establishment where the focus is on soil surface water. Research is needed to establish the optimum irrigation frequency for both establishing and established plants. Once crops are established, it should be possible to enjoy the potential benefit of SDI of reduced soil evaporation and increased water use efficiency.
4.2. Irrigation management in different soil types

Research is needed to provide guidelines for optimising irrigation frequency and amount in different soils and climates. Whilst the present research found responses to both irrigation frequency and amount, the interactions with soil type and climate were not clear enough to ‘fine tune’ recommendations to particular soil types or climates.

An investigation of yield performance of modified drip tape in range of soil type may allow vegetable growers to improve income and saving water. Research on irrigation scheduling for wide range of soil types and vegetable crop would be useful to reduce the environmental risk (runoff and deep drainage). These studies would include an assessment of the importance of more uniform crop maturity with modified SDI, and possible quality improvement in comparison to conventional SDI.

4.3. Nutrient management with SDI

Nutrient application through the modified SDI system is possible to increase nutrient use efficiency and reduce the risk of environmental impacts (deep drainage/nutrient rich runoff) in the Sydney region. A set of best management practices for modified subsurface drip irrigation with fertigation on vegetable production in intensive horticulture is required.

5. Conclusions

Crop establishment with SDI can be difficult, depending on the tape depth, soil properties and climate. Early designs for subsurface drip irrigation systems were mostly the same as for the surface drip system. But recent design development in the KISSSTM product aimed to improve crop establishment. The results demonstrate that, with this product, the surface soil water is wetter, and more uniform, than with conventional SDI. The improved soil water relations led to improved establishment and plant growth. The results also show that irrigation efficiency can be improved by using the modified SDI, and drainage reduced.
More frequent irrigation was confirmed to improve soil surface water and crop growth. The results show that frequent irrigation was just as important with modified SDI as with conventional SDI, although given the same irrigation management the modified product gave superior performance. With modified SDI it may be possible to apply less water and still obtain satisfactory establishment, but it appeared that both frequent irrigation and a high crop factor would be rewarded by substantially higher growth than with conventional SDI.

The management required to optimise growth and irrigation efficiency in different soils and environments needs to be developed by further research. The combination of modified SDI and ‘pulse irrigation’ should provide a useful improvement to horticultural practice, particularly for peri-urban production areas where the competition for water is intense, and the demand for good environmental performance is high.
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APPENDICES

Appendix 1. Maximum and minimum temperature of autumn, 2007 field trial

Appendix 2. Maximum and minimum temperature of spring, 2007 field trial
Appendix 3. Maximum and minimum temperature of glasshouse experiment

Appendix 4. Wet and dry bulb temperature of glasshouse experiment