DEVELOPMENT AND ASSESSMENT OF AN AUTOMATIC SHORT FURROW IRRIGATION SYSTEM

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of the degree of MSc Eng

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ABSTRACT

Automated short furrow irrigation (ASFI) is a prototype irrigation system that has the potential to be robust and relatively low-cost, with highly effective and efficient water use. ASFI has low energy requirements because the pressure at the field edge is relatively low, typically 70 kPa (or 7 m) as compared with approximately 150 kPa for drip and 400 kPa for dragline systems. However, at project onset, the only type of ASFI system tested was Micro-furrow which was, among other problems, not robust. The aim of this project was, therefore, to develop, implement and evaluate a suitable ASFI system and to compare the system to a reference sub-surface drip (SSD) irrigation system with sugarcane as the test crop. This process resulted in the development of a boot and piston valve, which was used to automatically control the flow between specific plots. The valve was then implemented, as per design, in the ASFI system at a trial at the University of KwaZulu-Natal's Ukulinga research farm. Irrigation events were scheduled according to *SAsched* with the aim of applying equivalent amounts of water to both the ASF and SSD treatments. The testing and evaluation included irrigation uniformity tests and the crop yields. Evaluation of selected furrows in the ASFI treatment showed a low quarter distribution uniformity (DU_{lq}) range between 72 % and 80 %. This is considerably better than approximately 60 % for conventional furrow irrigation. However, the *DU* for ASFI could be improved to above 90 % if the slope was reduced from 1:40 to approximately 1:250. Both the harvested tons per hectare and sucrose content results were evaluated using a one-way statistical analysis with differences between the results deemed to be insignificant. Therefore, the ASFI performance in terms of harvest data for the Ukulinga trial could be described as "similar to" SSD irrigation. A 10 ha sample ASFI system was designed and compared in economic terms with a respective SSD system. Although further piping options can be explored in order to reduce the capital costs of the ASFI system even further, ASFI was considerably more cost-effective than the SSD system in terms of operating and fixed costs per hectare. The ASFI irrigation system, although having some initial maintenance requirements in insuring all furrows performed properly, required no other maintenance throughout the year in the Ukulinga trial. The drip system, however, required laterals to be flushed and leaks to be repaired. It is therefore believed that the ASFI system meets the required objectives of the project in that it is robust, low-cost (both operating and fixed) and able to supply water efficiently and effectively.

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1. INTRODUCTION

South Africa is classified as a water scarce and semi-arid country (Badenhorst *et al.*, 2002; Perret, 2002). The demand for water was estimated to exceed supply in 10 of the 19 water management areas in South Africa in 2000 (DWAF, 2004a). It is, therefore, necessary to identify the major water users and to improve the water use efficiencies in those sectors. In 2000 the agricultural sector was estimated to account for approximately 62 % of the total water use in South Africa (DWAF, 2004b). With the increasing pressure on the limited water reserve and an increase in competition for water between the various economic and environmental sectors, the irrigation sector, in particular, is being pressured into being more accountable for the water used in the sector (Ascough, 2005; Griffiths, 2007). According to Armitage *et al.* (2008) changing or upgrading of irrigation systems needs to be analysed from both a hydrological and an economic perspective. These irrigation systems can be delineated into four main categories, namely:

- flood or surface (basin, border and furrow);
- mobile irrigation (centre pivot, linear move and travelling gun);
- sprinkler (dragline, quick coupling, big gun and permanent sprinklers); and
- micro irrigation (micro sprayers and drip) (ARC, 2003).

Each of the irrigation systems within these categories has potential advantages and disadvantages (discussed in Section 2.4 of this document) under various conditions, such as soil type, crop type and farmer requirements. In general, however, many systems are not optimal. For example, drip irrigation although potentially highly efficient, is often not financially feasible and/or can be overly complex from a management perspective. The development of a system that is highly efficient and competitive economically would be extremely valuable to both subsistence and commercial farmers. The main hypothesis of this study is that Automated Short Furrow Irrigation (ASFI) has the potential to be a robust, relatively low-cost system with a highly uniform and efficient irrigation application. With ASFI, water is applied sequentially to sets of relatively small and short furrows of approximately 30 m in length. By automating the sequencing of the short furrow sets, with accurate control of the flow of water into the furrows, labour requirements are minimal and system performance can potentially be enhanced. With the relatively short furrows, the distribution uniformity or evenness of applied water should be very high under a wide range of conditions and, since only a very small proportion of the soil surface is wetted, there should be relatively low soil evaporation losses. The system layout, including piping and emitters, needs to be configured in such a way that although the irrigation furrows are short, relatively high machine operating efficiencies are possible.

The objective of this project was, therefore, to develop and evaluate a prototype, automated system for Short Furrow Irrigation (SFI). This project was an integrated study encompassing a range of developments, with focus on the development of the system as a whole rather than concentrating on specific facets of the system. In order to meet the main objectives of the project, the following main tasks were performed and are described in this dissertation:

- A theoretical analysis of ASFI in the context of other irrigation systems and the identification of design requirements and design tools was undertaken (Chapter 2).
- A prototype ASFI system for sugarcane was designed and commissioned in a field trial at Ukulinga, the University of KwaZulu-Natal research farm, including furrows, pipe network and the novel, automatic control valve to facilitate the operation of the system (Chapter 3).
- The performance of the ASFI system relative to a reference drip irrigation system was assessed by evaluating agronomic, economic and engineering considerations. These included: irrigation performance tests (Section 4.2), soil moisture monitoring analysis (Section 4.3), a yield analysis of the harvested crop (Section 4.4) and an economic comparison of ASFI and sub-surface drip (SSD) irrigation systems (Section 5.4)
- Recommendations for application of ASFI and/or further research and development are summarised in Chapter 6.

2. IRRIGATION SYSTEMS AND PERFORMANCE

This chapter contains the project background by placing ASFI in the context of other irrigation systems, in particular within traditional furrow irrigation. The chapter begins with performance indicators that are used to analyse the performance of irrigation systems. Traditional furrow irrigation is then introduced with advantages and disadvantages of the system being discussed. Many of the disadvantages of traditional furrow irrigation are overcome with SFI. However, SFI also has a number of disadvantages. Many of these disadvantages could, however, be overcome by automating SFI. A prototype system for automating SFI named "Micro-flood" is therefore introduced. The concepts of micro-flood are reviewed and issues with the system are highlighted together with potential solutions.

2.1 Irrigation Performance Indicators

The effectiveness of irrigation systems is a descriptive term that incorporates quantifiable terms such as the Application Efficiency (*AE*) and Distribution Uniformity (*DU*) and depends on how much water is stored in the root zone, the water losses below the root zone, the uniformity of the applied water and the associated proportion of a field which remains in deficit or is under-irrigated (Walker, 2003). These concepts are illustrated with a typical surface irrigation profile in Figure 2.1.

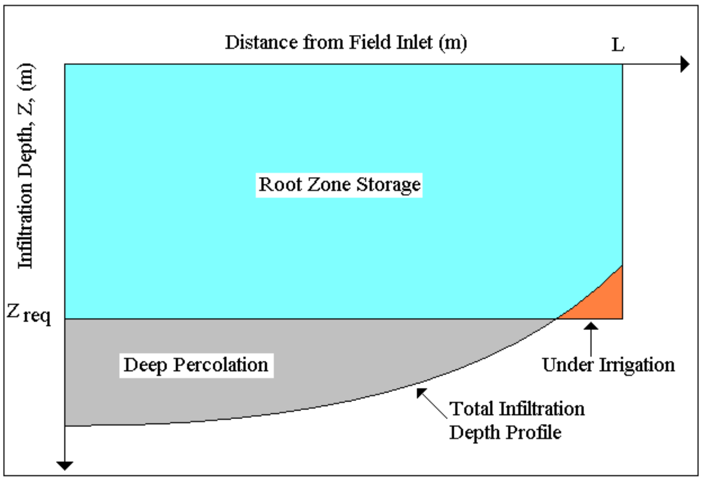

Figure 2.1 Total infiltration depth profile for a field (after Walker, 2003)

Typical performance indicators used for furrow irrigation are the: *DU*, *AE* and Requirement Efficiency (*RE*). However, definitions of these terms can vary slightly. For the purposes of this study, these indicators are defined as proposed by Merriam and Keller (1987) and used in the surface irrigation simulation software, SIRMOD III (Walker, 2003).

DU is the average irrigation depth of the least-irrigated 25 % of the field divided by the infiltration depth over the whole field (Walker, 2003). The equation for DU is given as:

$$DU = \frac{Z_{lq}}{\frac{V_{rz} + V_{dp}}{L}} \tag{2.1}$$

where: Z_{lq} = depth of infiltrated water in the least-irrigated 25 % of the field (m).

V_{rz} = volume of water per furrow spacing that is actually stored in the root zone (m^3/m).

V_{dp} = the volume of water per furrow spacing that percolates below the root zone (m^3/m).

L is the field length (m) (Walker, 2003).

The *AE* is the volume of water per furrow spacing that is stored in the root zone divided by the total volume of water applied per furrow spacing (Walker, 2003). *AE* is defined as:

$$AE = \frac{V_{rz}}{V_{rz} + V_{dp} + V_{tw}} \tag{2.2}$$

where: V_{tw} = volume of water per furrow spacing that flows from the field as tail water (m^3/m).

RE is the volume of water that is stored in the root zone per furrow spacing divided by the root zone storage volume per furrow spacing (Walker, 2003). *RE* is defined as:

$$RE = \frac{V_{rz}}{V_{rz} + V_{di}} \tag{2.3}$$

where: V_{di} = volume of water per furrow spacing that is represented as under-irrigation (m^3/m).

DU, *AE* and *RE* are important parameters that need to be analysed simultaneously to ensure effective and efficient application of water to the soil. Ideally, it is necessary to apply water uniformly, at a required depth, to ensure that the system can efficiently meet the crop water requirements. Determining the required irrigation depth is important and needs to be matched with crop water requirements and soil water holding characteristics. When the irrigation water application amount is not well matched to soil water holding characteristics, system performance will be poor because of either:

- excessive crop stressing if the soil moisture is depleted to the level required for applying larger irrigation depths; or
- inefficient irrigation with unnecessary runoff and deep percolation losses and possibly even related drainage problems (Lecler, 2004a).

Excessive runoff and deep percolation losses are significant factors associated with low field level irrigation application efficiencies, and are largely a result of poor water management and/or system design. A major problem is incorrect matching of irrigation water applications to crop water demands. Runoff and deep percolation can be reduced considerably by utilising appropriate irrigation scheduling, thus ensuring that water is applied in amounts not exceeding the soil water storage capacity and before crop stress occurs. The results of non-uniform irrigation applications are water wastage and variable and decreased crop yields (Lecler, 2004a).

2.2 Furrow Irrigation

Surface irrigation accounts for 90 % of irrigation worldwide (ARC, 2003). Surface irrigation is the introduction and delivery of water to a field by the gravity flow of water over the soil surface. Components of a surface irrigation system include the water source, the conveyance system, the field canal and/or pipe system, the infield water use system and the drainage system (Savva and Frenken, 2002). Typically, there are water losses in the conveyance system between the water source and point of application in the field. These losses can be a result of infiltration as well as evaporation. In furrow irrigation, the infield water use system, or furrows, involves running water into small channels that carry the water as it advances down or across the field slope (Booher, 1974). Furrow irrigation can either have open or blocked downstream conditions. In open systems, when water has reached the end of the furrow, it will often run into a drainage or tail water re-use system (Walker, 2003) For blocked-end furrows, water will begin to pond when the water reaches the furrow end (Yonts and Eisenhauer, 2007).

2.2.1 Factors impacting the performance of furrow irrigation systems

In furrow irrigation, the performance indicators, *DU*, *AE* and *RE* are influenced by infield factors such as furrow inflow-rate, furrow lengths, furrow shape and slope, and soil characteristics including surface roughness and soil infiltration properties (Hanson, 2001). Slope, field length and flow-rate can be adjusted. However, the soil characteristics are difficult to control and measure as they vary spatially over the field as well as over the growing season as a consequence, for example, of antecedent soil moisture conditions (Hanson, 2001). The soil characteristics that need to be obtained before deciding on the system layout are the soil type and texture, soil depth, the possibility of soil crust formation, and the soil infiltration characteristics (ARC, 2003).

The ideal furrow shape depends on the stream size, soil types and crops. Clay soils require a wide, shallow furrow to achieve a large wetted area so as to promote infiltration (Kay, 1986). Narrow, deep V-shaped furrows are used on sandy soils to reduce the soil area through which water percolates. Sandy soils are, however, less stable and tend to collapse (Brouwer *et al.*, 1988). In addition, the furrow spacing should comply with the tractor wheel spacing so that infield mechanical procedures can continue (ARC, 2003).

Furrow irrigation can be used on flat land and on mildly sloping land with a maximum gradient of 1:200. An uneven gradient will result in uneven wetting along the furrow (Brouwer *et al.*, 1988). When it is practical, furrows should be straight and parallel to the field edge and aligned down the main land slope. If the main slope of the land is too steep, furrows can be aligned across the main slope, thus reducing the furrow slope (Crosby *et al.*, 2000).

The irrigation times for traditional furrow irrigation are long with large depths of water of greater than 50 mm being applied with a cycle time of approximately 7 to 10 days between irrigation events. Flow-rates must be balanced against soil type and slope to minimise erosion, and against field slope and length to ensure a reasonable cut-off time. Operating at a flow-rate either above or below the design flow-rate can result in ineffective and non-uniform water applications (Ley, 2003).

2.2.2 Water application phases and irrigation performance

To ensure high efficiencies and uniformities are achieved using un-pressurised irrigation systems, such as furrow irrigation, all parts of the field should receive water for near equal time periods with minimal losses due to deep percolation and runoff (Ley, 2003). This time is known as the contact time or intake opportunity time and is illustrated in Figure 2.2. There are four phases in furrow irrigation. These are:

- the advance phase;
- the storing or ponding phase;
- the depletion phase; and
- the recession phase (Savva and Frenken, 2002).

As illustrated in Figure 2.2, the advance phase commences when the irrigation event is first applied to the furrow and ends when it reaches the downstream end of the furrow. The furrow inflow-rate must be greater than the soil infiltration rate so that water infiltrates into the soil at the same time as it advances along the furrow. The storing phase commences when the water arrives at the bottom end of the furrow, yet furrow inflow is continued. This phase will not take place if inflow is stopped before the advance front has reached the end of the furrow. After the inflow is cut-off, some water continues to infiltrate, some water ponds and some excess water is collected as runoff. When the inflow into the furrow is stopped, the depletion phase commences, with water continuing to infiltrate, pond and runoff. When water starts receding from the start of the furrow and continues to the bottom of the furrow, this is known as the recession phase. The time difference between the advance front and recession front is the contact time (Basset *et al.*, 1983).

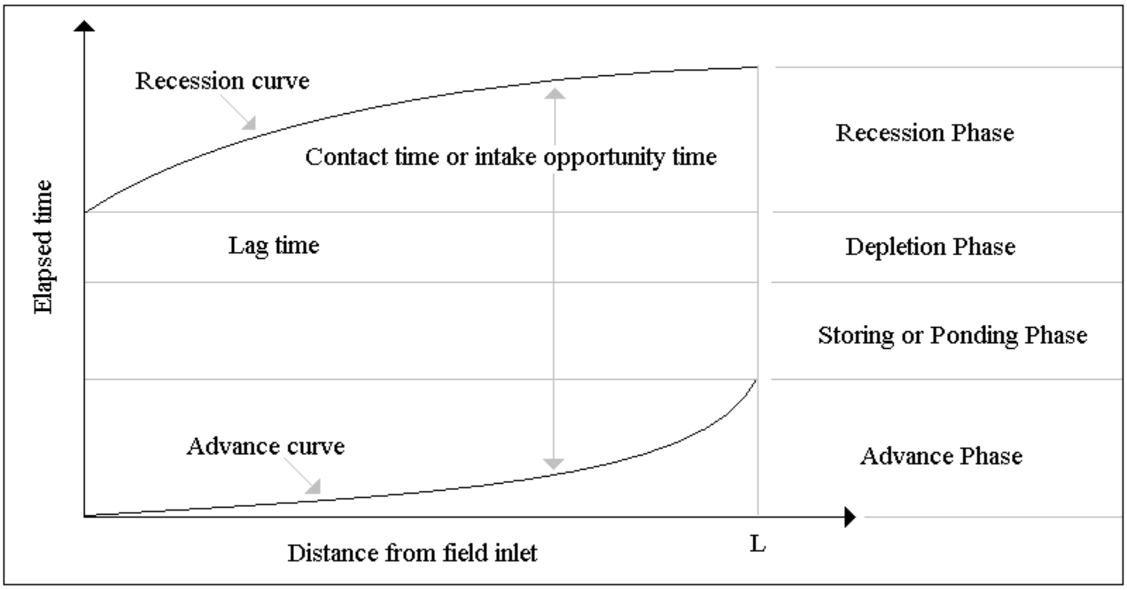

Figure 2.2 Surface irrigation phases (Basset et al., 1983)

Extensive research has been conducted as to which factors affect furrow irrigation performance and result in the generally low DU and AE values. Table 2.1 contains a summary of the factors that affect uniformity of furrow irrigation and relates the factors to uniformity components such as opportunity time, as illustrated in Figure 2.2, and soil infiltration characteristics.

Table 2.1 Factors that affect uniformity of furrow irrigation (after Burt et al., 1997)

Uniformity component	**Factors causing non-uniformity**
Opportunity time differences down a furrow	Extent of ponding Flow-rate and duration Slope and roughness Furrow cross-sectional shape Furrow length
Opportunity time differences between furrows	Different day/night irrigation set times Wheel row compaction/no wheel compaction Different furrow flow-rates
Different infiltration characteristics for individual furrows	Different degrees of compaction due to tractor tyres and tillage
Different infiltration characteristics across the field	Different soil types Soil chemical differences Texture differences of soils
Other opportunity time differences throughout a field	Non-uniform land preparation
Difference in day and night intake rate	Viscosity changes due to temperature changes
Infiltration rate differences due to differences in wetted perimeter	Slope changes or restriction to flow along the furrow

Lecler (2004a) conducted tests on furrow irrigation performance in Zimbabwe. Furrow irrigation performance was negatively impacted by large variations in the amounts of water applied to individual furrows, and generally excessively high applications of water. The large water applications did compensate, to a degree, for the variations in applied water between and down the furrows, however, efficiencies were compromised and may result in other problems, including raised water tables and increased soil salinity levels (Lecler, 2004a).

Magwenzi (2000) evaluated the performance of furrow irrigation in the Swaziland sugar industry. *DU* values averaged 84 % and ranged from 67 % to 97 %. *AE* ranged from 48 % to 74 % with an average of 67 %. Typical *AE's* for furrow irrigation systems range from 45 % to

60 %, which is relatively inefficient when compared to other irrigation systems (Ley, 2003). *AE* can be increased to range from 70 % to 85 % by using careful management and improved water control (Ley, 2003). However, with furrow irrigation, improved water control is often difficult and may be constrained by other factors, such as the available water supply being insufficient to supply the flow requirements for the furrow. *AE* can also be improved by using shorter furrows as in SFI (Crosby *et al.*, 2000).

2.3 Short Furrow Irrigation (SFI)

Crosby *et al.* (2000) conducted a number of SFI experiments in South Africa and their results, shown in Table 2.2 and Table 2.3, indicated that a high *DU* is possible for SFI at various furrow inflow-rates. Crosby *et al.* (2000) stated that for most flood irrigation systems, it is crucial that the land is well-prepared and cultivated every season so as to ensure uniform gradients and to remove hollows, furrows and ridges which will impede the flow. For small-scale farmers, ensuring uniform slopes is exceptionally difficult as there is a lack of power for tillage purposes. However, SFI is not nearly as sensitive to these factors as conventional flood irrigation is. SFI has the advantage that water advances rapidly down the furrow, ensuring even distribution in even sandy soils with a high infiltration rate (Crosby *et al.*, 2000). Therefore, SFI results in a very uniform water distribution across the field, even where the gradient varies or there is an inconsistent flow-rate. These variations in flow-rate and gradient would make the more conventional methods of flood irrigation extremely difficult (de Lange, 1997).

Table 2.2 Possible Distribution Uniformities (*DU*) on a loam soil at two different flow rates (after Crosby *et al.*, 2000)

Soil: Loam			**Gradient**			
			1 m : 300 m		Zero	
			L = 10 m	L = 20 m	L = 10 m	L = 20 m
Flow-rate (m^3/h)	5 m^3/h	*DU* (%)	72	89	86	87
	10 m^3/h	*DU* (%)	90	80	91	91

DU is the average irrigation depth of the least-irrigated 25 % of the field divided by the infiltration depth over the whole field.

Table 2.3 Possible distribution uniformities (*DU*) on a sandy soil at two different flow rates (after Crosby *et al*., 2000)

Soil: Sand			**Gradient**			
			1 m : 300 m		Zero	
			L = 10 m	L = 20 m	L = 10 m	L = 20 m
Flow-rate (m^3/h)	5 m^3/h	*DU* (%)	80	82	95	85
	10 m^3/h	*DU* (%)	75	90	98	95

DU is the average irrigation depth of the least-irrigated 25 % of the field divided by the infiltration depth over the whole field.

Despite the high *DU* values of SFI in terms of furrow irrigation, there are a number of disadvantages to using SFI. These include the following: mechanised cultivation for SFI is difficult, water losses occur in the supply furrow and it is a relatively labour intensive system (ARC, 2003). Lecler (2006) suggests that these disadvantages can be potentially overcome by automating the SFI system. Water losses in the conveyance system of an ASFI system could be addressed by using pipes rather than supply furrows (Lecler, 2006). This is due to the use of pipes becoming economically feasible as a result of the smaller flow-rates. As a result of the pressure being low, low-cost flexible piping could also be used, as suggested by Austin (2003a). In addition, with ASFI operation is largely automated and there are no pipes that need to be moved between irrigations or siphons that need to be primed and thus labour requirements could also be reduced (Lecler, 2005). The hydraulic design of ASFI could also be more rigorous with improved control of flow-rates into the individual furrows (Lecler, 2006).

To the author's knowledge, there was no suitable ASFI system in widespread operation at the commencement of this project. Due to the newness of ASFI, little research has been conducted on ASFI other than Austin (2003a; 2003b), a retired engineer who proposed a system for solving this problem on his internet website www.waterright.com.au.

2.3.1 Micro-flood: a type of Automated Short Furrow Irrigation (ASFI)

Small-scale technology is required in South Africa to improve the ability to design and develop new and appropriate SFI systems (de Lange, 1997). Austin (2003b) proposed a potential solution to this problem, named micro-flood. Austin (2003b) describes the Micro-flood concept as extremely simple. Water supply is from the mainline, a pipe running down the length of the field, with tap off points at specific points along the length. Laterals with emitters are used to distribute the water across the width of the field. Initially the system works like a conventional flood system with water being distributed to the first tap off point, as illustrated in Figure 2.3. However, when the flow enters the next section, the water is diverted down the mainline to the next tap off point. Only small amounts of water are applied during each irrigation event. The soil is not totally saturated resulting in no water loss, with the soil moisture being maintained within desired ranges thus resulting in optimum production (Austin, 2003b). Austin (2003b) reports that the use of Micro-flood can increase production by 40 %.

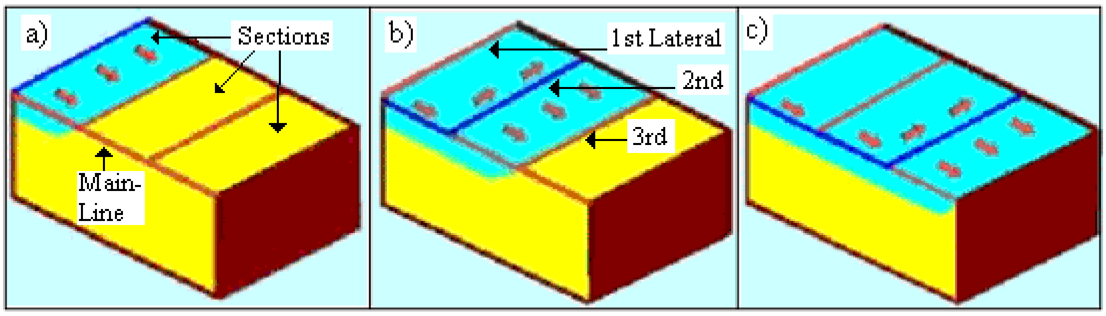

Figure 2.3 The systematic progression of Micro-flood irrigation (after Austin, 2003b)

Traditional flood irrigation systems usually apply large depths of greater than 50 mm of water per irrigation application every 5 to 10 days (Griffiths, 2007). However, Austin (2003b) proposed that Micro-flood would be better for the following reasons:

- Plants respond better to smaller and more regular irrigation events, associated with Micro-flood, resulting in an increased productivity. Micro-flood systems are designed to apply a fixed amount of water of approximately 5 mm per irrigation event, depending on the water-holding capacity of the soil (Austin, 2003a).
- Micro-flood irrigates short sections at a time, in sequence, resulting in no water passing beyond the root zone (Austin, 2003c).
- Evaporation losses are low as the irrigation time for each furrow set is only a few minutes and only a small portion of the soil surface is wetted (Austin, 2003c).

To summarise, reducing the furrow length results in a high *AE* and *DU*, even at very low flow-rates (Austin, 2003b). The low water requirements result in many water sources which are too small for effective flood irrigation to be used. Small, low-cost pipes can now replace the large open channels, resulting in significant water saving. Any soil types can be irrigated using Micro-flood as the furrow inflow-rate can be adjusted to match soil conditions (Austin, 2003a).

The system shown in Figure 2.3 requires a cheap and simple valve system to be used at the tap off points, so that each set of furrows can be irrigated in turn (Austin, 2003a). Colin Austin proposed a system of tilt valves and risers. The risers direct the water into the tertiary line by elevating the pipe so that the water needs to overcome a head. This is done by using an inverted U. The flow is diverted to the next block by using the tilt-valve to block the flow down the tertiary line, forcing the water over the riser. The total area is therefore irrigated by each valve closing in turn, once each set of furrows has received sufficient water (Austin, 2003b). The valve, known as the tilt valve and shown schematically in Figure 2.4, works as follows. A small bleed tube, attached to the tertiary line, is used to fill the L- or U-shaped tilt valve. Before irrigation, the valve is balanced in the open position. When the irrigation event commences, the water starts to fill Section A, thus continuing to hold the valve open as represented in Figure 2.4. The valve will stay open throughout the irrigation of that set of furrows. The valve continues to fill, filling Section B as well. When the weight of the water in Section B is greater than the weight of the water in Section A, the valve pivots, forcing the water in Section A to rush into Section B, resulting in the flexible tubing being snapped shut (Austin, 2003b).

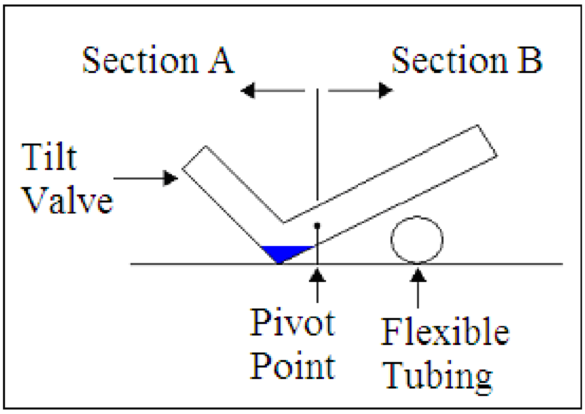

Figure 2.4 Colin Austin's tilt valve (Jumman and Mills, 2005)

Jumman and Mills (2005) conducted experiments on a number of variations of the tilt valve. The findings of these experiments were that the tilt valve failed to shut off the flow completely down the tertiary line. This was due to insufficient force applied by the valve on the flexible tubing. Achieving the correct cut-off time was also found to be extremely difficult. This would result in a poor *DU* and *AE*. Due to the delicate balance of the system, as well as the sensitivity of the system to uncontrolled variables such as twists in the pipe, the system was deemed impractical (Jumman and Mills, 2005). The riser setup was also problematic. The theory behind the riser setup is that while the water is flowing down the lateral, there is a hydrodynamic head at the riser. Once the valve shuts-off flow down the lateral, there would be no flow in the system resulting in a static head at the riser, allowing the riser to be overcome. In other words, the riser uses the difference between the hydrostatic head and the hydrodynamic head to control flow between the blocks. This difference is extremely small. Therefore, it is extremely difficult to position the uppermost point of the riser correctly. A variation in the system inlet pressure will result in a failure of the system (Jumman and Mills, 2005). There is therefore a need to investigate various valve alternatives that are suitable for flow control in the ASFI system.

2.3.2 Automation

A number of alternate valve options which may be suitable for ASFI were investigated. The valves with the most potential are the focus of this section. The first alternate valve considered was used in a gated pipe system. This system was designed for conventional furrow irrigation. A flow-through gated pipe system consists of a single gated pipeline installed in a series of level segments at the top end of the field (Humpherys, 1986). Each segment is for one irrigation set with a stair-step drop at its lower end. A semi-automatic butterfly valve is located downstream of the drop. The water only occupies 60 to 75 % of the pipe cross sectional area, with the gates near the top end of the pipe, above the water surface for all upstream sets. The valve, located just below the drop, is used to release water to the next downstream set (Hoffman *et al.*, 1990). Humpherys *et al.* (1983) developed a torsion spring operated valve which was commonly used to release the water to the next downstream set. A three-way valve can also be used to split the field up into sections (Fischbach and Goodding, 1971). The three-way valves developed by Fischbach and Goodding (1971) and Humpherys and Stacey (1975), used in the above systems, show potential as alternatives for the tilt valve. Fischbach and Goodding (1971) used an inflatable rubber diaphragm to stop the flow of water through the valve. A three-way pilot valve controls the air in and out of the diaphragm of the automatic valves (Fischbach and Goodding, 1971). Humpherys and Stacey (1975) use a similar bladder valve with a three-way pilot valve that controls the filling and emptying of the bladder.

The above valves were later developed into the surge valves. The surge valve is a valve which has been specifically designed for surge flow irrigation, a system whereby a field is irrigated in short surges. There are two main surge flow valve types: the bladder valve and the mechanical valve. The bladder valve uses an inflatable bladder in each of the branches in the T-shaped valve. The bladder inflates to block flow in a branch and deflates to let water through the other branch. These bladders can either be inflated by water pressure in the pipeline or by air pressure. The mechanical surge valve uses a butterfly disk valve to control the flow direction in the T-piece. This valve can be powered by electricity, air pumps or water pressure (Henggeler *et al.*, 1986). Jumman and Mills (2005) suggested that by making slight alterations to these valves, such as setting the time period that each side is open, could result in a system which is suited to short furrow irrigation. However, the cost of 8 and 10 inch valves ranged from \$ 755 to \$ 895 with the controller costing between \$ 545 and \$ 1015 depending on the controller's features (Nishihara and Shock, 2001). These costs were considered excessive, with at least 4 valves required per hectare under ASFI.

A more cost-effective potential valve option was developed by Jumman and Mills (2005). The valve is known as a piston valve, which, with a couple of modifications, may be suitable for ASFI. The piston valve is connected on to the lateral of the ASFI system and directly replaces the tilt-valve from Colin Austin's system. This valve, therefore, does not negate the need for a riser. The mainline will therefore run perpendicular to the upstream side of the valve in Figure 2.5. A bleed tube is used to fill water into a bucket. The weight of the water in the bucket opposes the tension in the spring, pushing the piston down to the critical level, as indicated in Figure 2.5. Once the piston moves past the critical level, the pressure in the system pushes the piston down onto the O-Ring, snapping the valve shut. The flow in the lateral is therefore shut off and water flows over the riser. The bucket drains when the valve closes. The valve is kept in the closed position by the pressure of the water in the mainline. Hence, when flow in the mainline stops, the tension spring is able to pull the piston up and reset the system (Jumman and Mills, 2005).

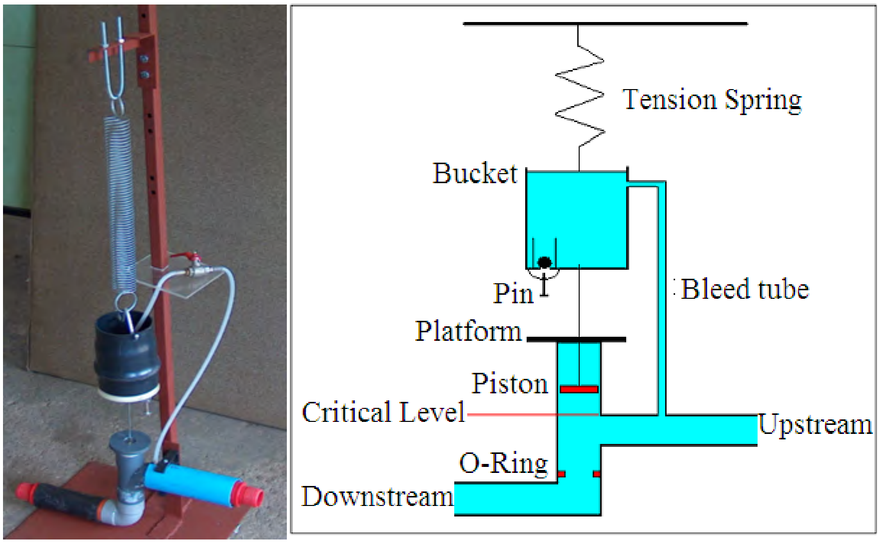

Figure 2.5 The piston valve (Jumman and Mills, 2005)

The piston valve was assessed by Jumman and Mills (2005) and was found to be successful with regard to completely shutting off flow down the lateral. The ball valve on the bleed tube ensured the correct cut-off time. The piston valve does not require any electrical components, which greatly reduces both the initial and running costs. This would also eliminate the need for an electrical supply which would be beneficial as many users are in rural areas, without power supply. The piston valve is more compact and robust than the tilt valve. The piston valve was also easier to connect to the pipe network. Eliminating the need for the riser reduces the number of components and therefore the cost of the system (Jumman and Mills, 2005). The piston valve was the most suitable valve out of all the valves investigated for the ASFI system. However, before further valve and system developments were undertaken, it was necessary to theoretically assess how ASFI competes with commercial irrigation systems.

2.4 Conceptual Comparison of ASFI with Other Irrigation Systems

Factors to consider when comparing irrigation systems include:

- system capital and maintenance costs;
- the efficiency and uniformity of the irrigation application;
- the efficiency of the system from the storage structure (e.g. dam) to the soil surface;
- the life expectancy of the system; and
- labour requirements.

The ARC (2003) placed approximate values to these factors in 2003, with results summarised in Table 2.4. It is important to note that the costs were estimated and are included for comparative reasons. Capital costs for systems can vary significantly depending on factors such as pump requirements, distance of water source from the field edge, pipe trenching and land levelling requirements. When analysing each of the factors it appears that each system has advantages and disadvantages. Furrow irrigation has the lowest estimated capital costs.

Table 2.4 Comparison of different irrigation systems (ARC, 2003)

Irrigation Group		**Irrigation System**	**Estimated Capital Costs [R/ha$\times 10^3$] (2003)**	**System Efficiency [%]**	**Life Expect-ancy [years]**	**Labour Require-ments [ha/ labour]**	**Annual Maintenance Costs [% of capital cost]**
Flood		Furrow	5-6	60-80	10	10	5
		Border	7-9	60-80	15	15	5
		Basin	6-9	60-80	20	12	5
Static	Sprinkler	Permanent	14-16	75	15	50	1
		Dragline	10-12	65	10	25	4
		Quick Coupling	9-12	70	12	20	3
		Hop-along	11-13	65	12	25	2
		Big gun	8-9	65	10	20	4
		Side roll	11-13	65	12	25	2
		Boom	8-10	65	15	25	4
Static	Micro	Drip	18-20	90	5-15	30	2
		Subsurface drip	20-22	95	10	25	3
		Micro sprinkler	14-17	80	10	30	3
		Micro Sprayer	22-25	80	15	30	3
Mobile		Travelling gun	9-11	65	10	25	6
		Travelling boom	10-12	65	12	30	6
		Centre pivot	18-20	80	15	100+	5
		Linear move	30-35	80	15	100+	6

Mobile irrigation systems are either expensive (e.g. Centre Pivots and Linear Move systems) or have high energy requirements (e.g. travelling gun systems). Static irrigation systems have relatively high working pressure of between 20 and 40 m for a permanent system, to even higher for systems such as big gun irrigation. This high pressure can dramatically increase the operating cost of a system. Micro irrigation systems are very expensive (ARC, 2003).

System efficiency is defined in Figure 2.6 to be the efficiency of the system between the irrigation dam and the soil surface. This therefore does not include the losses between the soil surface and the root zone. It is important to note that different publications define the various terms differently. For example, the field application efficiency shown in Figure 2.6 and proposed by the ARC (2003) is equivalent to the *AE* proposed by Mirriam and Keller (1987) and used in Chapter 2.1 The *AE* proposed by Mirriam and Keller (1987) in Chapter 2 is therefore different to the *AE* shown in Figure 2.6 and proposed by the ARC (2003). However, as a result of different water application methods for each irrigation system, it is extremely difficult to find a single measure to evaluate each system. The system efficiency, although giving a good indication as to system performance, can therefore be misleading. The system performance can also change over time. For example, factors could affect the performance of a SSD system, as described in Section 2.4.2. The performance of the SSD system would therefore be substantially less than the 95 % efficiency suggested in Table 2.3.

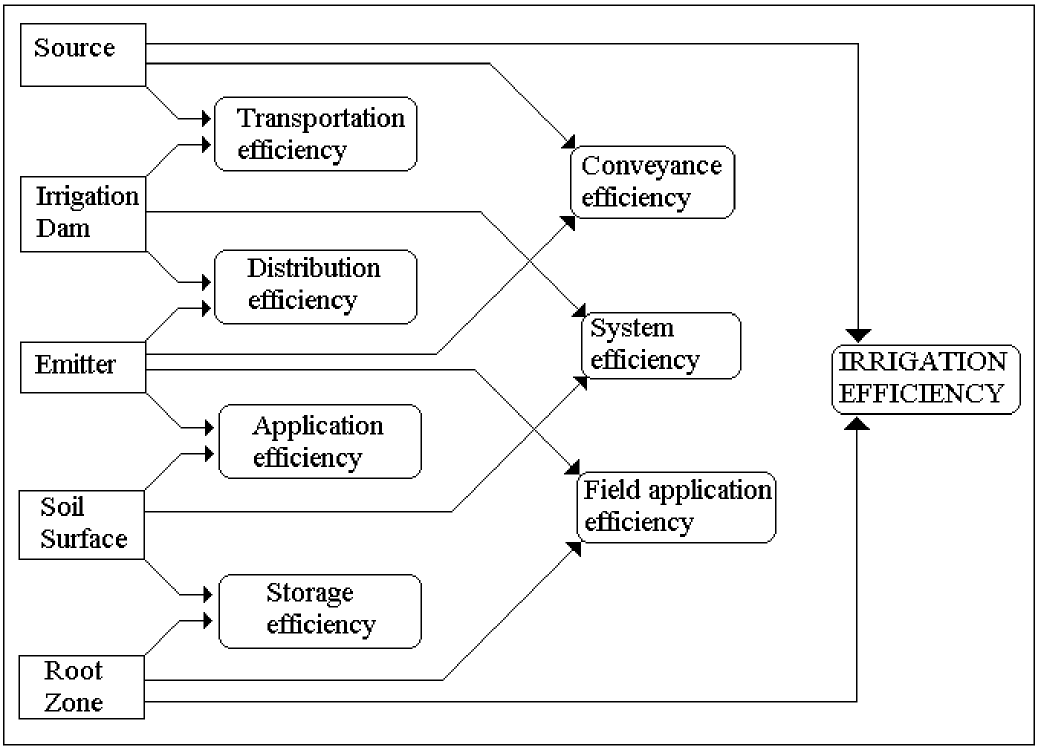

Figure 2.6 Irrigation Efficiencies (ARC, 2003)

Lecler (2006) suggests that the use of ASFI has substantial advantages and could potentially out-perform other types of irrigation systems in terms of irrigation efficiency, effectiveness and economic margins. If a suitable ASFI system is developed, it could have the potential advantage of the water application being reduced to only 15 mm per irrigation event, without the *DU* and *AE* being compromised and with relatively low soil water evaporation losses, compared to overhead sprinkler systems. The use of relatively small, frequent, uniform and low-loss irrigation water applications would allow a range of crops and soils to be irrigated with ASFI relatively efficiently and effectively (Lecler, 2005). At the onset of the project, these were, however, only theoretical hypotheses based on initial computer simulations. In addition, labour requirements could also be reduced with ASFI because operation is largely automated and there are no pipes that need to be moved or siphons that need to be primed (Lecler, 2005).

In the following sections, ASFI is theoretically compared to sprinkler and drip irrigation respectively. These systems were selected, as SSD irrigation provides the benchmark in terms of irrigation performance, while sprinkler irrigation provides a benchmark in terms of a widely used, cost-effective system that still produces good uniformities. These two systems were seen as the major rivals to ASFI.

2.4.1 ASFI compared to sprinkler irrigation

When sprinkler irrigation is used on small-grower projects, lack of independence has resulted in considerable problems. For example, when an upstream grower of a shared sprinkler system fails to maintain nozzles, repair leaks or set correct pressures, this leaves downstream growers who are distant from the pumps with much frustration, high energy bills and low yields (Cain, 2001). ASFI may provide the desired combination of low-cost and high-efficiency required for small-scale farmers and could allow the farmers to operate relatively independent of each other.

ASFI can be much more effective than sprinklers as sprinklers wet the entire surface area so there are significant evaporation losses, some during application and the rest by evaporation from the upper soil layers. Short furrows, by contrast, result in most of the water going straight to the useful zone by subsurface flow (Austin, 2003a). Sprinklers are often run for long time periods so as to minimise evaporation losses, whereas ASFI has shorter and more frequent irrigations, which could reduce deep percolation losses. ASFI and sprinklers both distribute water horizontally, however ASFI is gravity- rather than pressure-fed (Austin, 2003b). Wind has a negative influence on the *DU* of sprinkler irrigation (ARC, 2003) but will not influence ASFI.

Reinders (2001) conducted assessments on the performance of irrigation systems in the sugar growing areas of South Africa. The assessments consisted of 20 dragline, 3 floppy sprinklers and 4 centre pivot systems. The results are recorded in Table 2.5. The *DU* values for the dragline and floppy sprinklers are significantly lower than the *DU* norm of 75 %. Only 5 % of the dragline systems tested and 0 % of the floppy sprinklers tested, obtained the 75 % norm. 100 % of the centre pivots obtained the D*U* norm (Reinders, 2001). The *AE* in Table 2.5 appears to be the efficiency between the emitter and soil surface, as in Figure 2.6, and does not include losses between the soil surface and the root zone.

Table 2.5 Performance results for irrigation types (Reinders, 2001)

	Irrigation type		
Parameter	**Dragline**	**Floppy**	**Centre Pivot**
No. of systems tested	20	3	4
Average *DU* (%)	60	67	83
Average *AE* (%)	76	77	82
Design capacity (mm/day)	4.1	5.1	5.9

Crosby *et al.* (2000) conducted experiments in South Africa on pressurised systems for small-scale irrigation. The findings were that correct pressures in the system were required for the efficient operation of sprinklers. However, pumps rarely operate at specified design pressures. Other problems encountered were incorrect management and maintenance of stand times, non-matching sprinklers and therefore inconsistent application rates, defective or missing sprinklers and variations in pressure throughout the system. A major difficulty of small-scale farmers is in obtaining skilled advice on equipment selection and design (Crosby *et al.*, 2000). Crosby *et al.* (2000) also found that farmers forgot to move sprinklers, which resulted in over-watering in certain areas. Sprinkler wear and tear is not immediately visible as a worn sprinkler will continue to operate until it completely fails. However, the efficiency of sprinklers may be sufficiently reduced, long before failure. Worn nozzles can double application rates which, like leaking pipes, can cause water logging. The suitability of soils to sprinkler irrigation is also a major concern. Soil surface crusting is a problem throughout South Africa, with surface sealing resulting in infiltration rates as low as 2 mm/h. This is a disadvantage for sprinkler irrigation with poor water infiltration leading to ponding or runoff. Moving sprinklers in high density crops such as sugarcane is difficult, especially in obtaining the correct sprinkler position (Crosby *et al.*, 2000).

2.4.2 ASFI compared to drip irrigation

One of the major considerations when assessing whether to select a drip irrigation system is the capital cost, as illustrated in Table 2.4 from ARC (2003). However, SSD irrigation does provide a benchmark in terms of irrigation performance when developing a new irrigation system such as ASFI. There are still issues regarding the performance of drip irrigation and the way water is applied using this irrigation method.

Austin (2003b) proposes that ASFI has very high flow-rates compared to drip irrigation for a short time period, which results in a wider spread of water in the horizontal plane rather than the vertical direction. Austin (2003b) concludes that this benefits plant growth and may also reduce losses due to deep percolation (Austin, 2003b). Drip irrigation is considered an efficient system, however there are examples of inefficient drip irrigation systems due to mismanagement and maintenance problems (Koegelenberg and Reinders, 2001).

Reinders (2001) conducted assessments on 11 test sites for a total of 11 micro sprinkler and drip irrigation systems with an average *DU* of 68 %. With a *DU* norm set at 85 %, none of micro sprinklers and only 33% of drip irrigation systems evaluated met the norm. Koegelenberg and Reinders (2001) conducted studies in six regions of South Africa on the performance of drip irrigation systems under field conditions. The drip lines were recovered from the field and tested against new dripper lines in the laboratory, with results shown in Table 2.6. Dripper lines with regular type emitters generally had a reduced average discharge due to emitters being clogged. The increase in discharge of certain regular type emitters was as a result of a sharp object being used to open blocked emitters. The increase in discharge of 58 % of pressure compensated emitters were possibly due to objects being stuck between the compensating membrane and the labyrinth, or the compensating membrane losing some of its elasticity over time (Koegelenberg and Reinders, 2001). Water filtration is therefore an important component of drip irrigation which adds to the cost and complexity of the drip system (Lecler, 2005).

Table 2.6 Percentage of drip lines with emitter discharges deviating from the average discharge of new emitters (Koegelenberg and Reinders, 2001).

Emitter type	**Reduced discharge (%)**	**Average discharge (%)**	**Increased discharge (%)**
Regular	50	34	16
Pressure compensating	8	34	58

Other reported disadvantages of drip irrigation are that root diseases are more prevalent due to the root zone being almost permanently wet, the pipes and drip laterals in the field also impede cultivation and highly pervious soils cannot be irrigated by drip irrigation due to insufficient lateral movement of soil moisture (ARC, 2003).

Possible reasons for a farmer choosing to install ASFI over bucket-drip kits and other small scale innovations are:

- Traditional flood and SFI is used by many small-scale farmers (Lecler, 2005).
- Water application is visible where some drip and especially SSD systems have failed to reach a high level of efficiency due to users over-irrigating as a result of the water application not being visible (Lecler, 2005).
- ASFI does not require relatively sophisticated water filtration as is required in bucket drip systems. This is due to the larger emitter size used in ASFI, which is difficult to clog (Lecler, 2005).

2.5 Computer Models for ASFI Design

Simulation models can be used to assess and predict the potential improvement to furrow irrigation efficiency and performance as a consequence of changes in management variables. A number of models have been developed to simulate surface irrigation systems. Some of these models have been developed into user-friendly computer programs with the aim of being used by irrigation practitioners as decision support tools (Hornbuckle *et al.*, 2006). Of these, the most widely used software, which incorporate all the phases of a surface irrigation event, are SIRMOD (Walker, 2003) and SRFR (Strelkoff *et al.*, 1998). Meyer and Bowmer

(2005) report that Associate Professor Maheshwari from the University of Western Sydney evaluated a range of surface irrigation models, including SIRMOD and SRFR, to predict advance and recession times, runoff and volume balance error using field data of over 100 irrigation events for a range of field conditions. SIRMOD was found to be the most suitable for these field conditions with errors generally being less than 15 % (Meyer and Bowmer, 2005).

SIRMOD III provides simulation, evaluation and design capabilities for border, basin and furrow irrigation under either continuous or surge flow operations. The evaluation algorithm uses the "two point solution" which allows for the infiltration parameters to be computed from the input of advance front data (Walker, 2003). Inputs required for SIRMOD to simulate an irrigation event include infiltration characteristics, hydraulic resistance (Manning's *n*), furrow geometry, furrow slope, furrow length, inflow-rate and advance cut-off time. The most difficult inputs to determine adequately are the infiltration characteristics and the furrow inflows, which are also the most sensitive inputs in the SIRMOD model (McClymont *et al.*, 1996). Furrow infiltration characteristics are represented in SIRMOD with the Kostiakov-Lewis infiltration equation as described in Equation 2.4.

$$Z = kt^a + f_o t \tag{2.4}$$

where: Z = the cumulative infiltration (m^3/m furrow),

t = the time (min) that water is available for infiltration,

f_o = the steady or final infiltration rate ((m^3/min)/m furrow), and

a and k are fitted parameters (Walker and Skogerboe, 1987).

According to Kruger (1998), the infiltration rates in South Africa (RSA) are generally higher than those found in the United States of America (USA) caused by the climate being generally dryer and warmer than that of the USA, resulting in different geological and ground forming processes. This causes the range of soil intake families used in RSA to become extended compared to the range used in the USA, as illustrated in Figure 2.7, and these differences need to be considered when determining the soil infiltration characteristics in the RSA (Kruger, 1998).

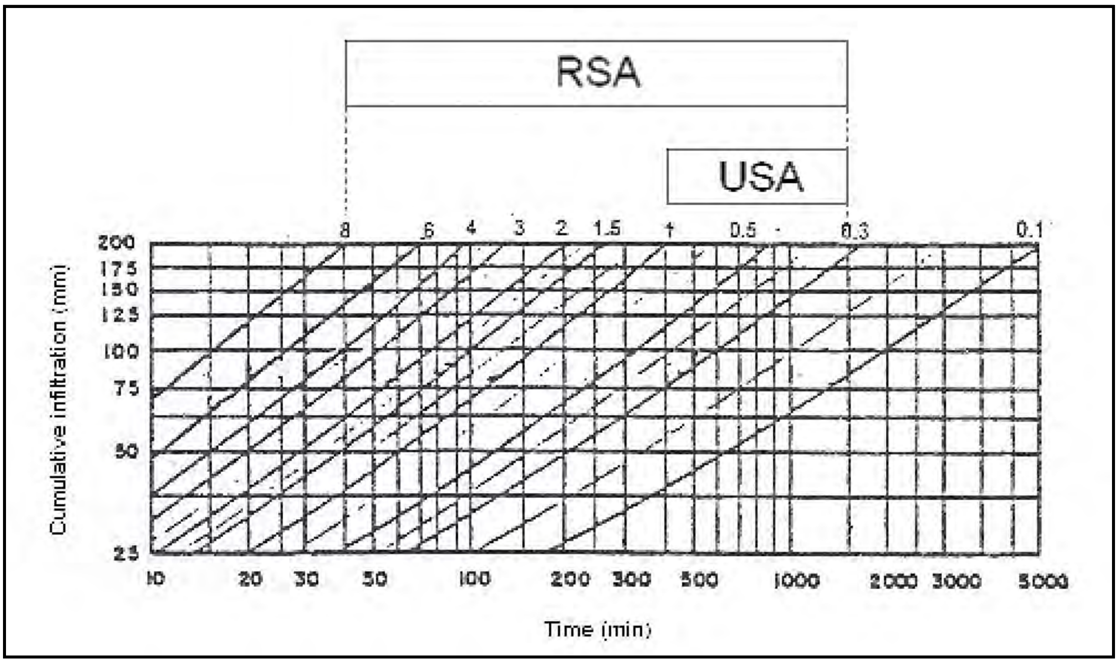

Figure 2.7 Comparison between USA and RSA soil ranges (Kruger, 1998)

SIRMOD III has a user-friendly interface with graphical outputs providing for easy interpretation of irrigation performance, which makes it a useful decision support tool for irrigation designers and managers. Outputs include a detailed advance/recession trajectory, runoff hydrograph, depth of water flow at the field end, *AE*, *RE* and *DU* (Raine and Walker, 1998).

Hornbuckle *et al.* (2006) conducted experiments in the Murrumbidgee Irrigation Area (MIA) in New South Wales and found that the greatest potential for SIRMOD to improve furrow irrigation is by direct usage by irrigators. This involves measuring the furrow inflow and advance characteristics to obtain the infiltration characteristics and then running SIRMOD to determine the optimal management regimes. This requires simple and cost-effective methods of determining the inflow and advance characteristics (Hornbuckle *et al.*, 2006). Hornbuckle *et al.* (2006) found that SIRMOD adequately predicted furrow irrigation for the soil conditions in the MIA, with infiltration volumes predicted by SIRMOD and measured infiltration volumes being highly correlated (r^2 = 0.9474).

McClymont *et al.* (1996) conducted an experiment for furrow irrigation of sugarcane in Australia and found that SIRMOD under-predicted the advance times by an average of 22 % and the measured infiltration volumes by an average of 16.9 %. This was attributed to a systematic error within the model which could be corrected by applying an appropriate calibration procedure (McClymont *et al.*, 1996). Raine *et al.* (1997) conducted experiments on surface irrigation in the Burdekin Delta in Australia and found that only small adjustments to the Manning hydraulic resistance were required to improve the accuracy of the SIRMOD predictions, indicating that the advance rates predicted by SIRMOD were similar to the field measured rates for this site. However, as a result of large variations in soil infiltration properties, both across the field and throughout the season, model predictions are only as accurate as the input data quality. Therefore, unless the input data is obtained from actual irrigation events and includes a measure of field variation, the model should only be used to show trends (Raine *et al.*, 1997).

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Chapter 2 has accomplished the first goal of the project: a theoretical analysis of SFI in the context of other irrigation systems and the identification of design requirements and design aids/tools. Current irrigation systems each have advantages and disadvantages which would result in each of these systems being selected under different circumstances. Economic and performance measures are used to assess the most suitable option in each circumstance. It is unlikely that the selected system would be optimal in both of these measures and either the system performance or cost will be compromised. ASFI appears to have the potential to be optimal in terms of both system costs and performance under most circumstances. However, these are theoretical assumptions which need to be tested and verified in a field trial. The focus therefore shifted to the second goal of the project: the development of a prototype ASFI system for sugarcane, including furrows, pipe network and the novel, automatic control valve to facilitate the operation of the system.

3. UKULINGA FIELD TRIAL

The procedures undertaken in the field trial can be categorised into four phases. The first phase was the initial development and testing phase. This phase included determining the system requirements, conducting preliminary field tests and developing a prototype valve to be used in the field trial. The second phase was the trial establishment phase which comprised of the irrigation designs for both the SSD irrigation and the ASFI systems used in the field trial, the field layout, crop planting and irrigation installation. The third phase is the trial monitoring and management phase which included the irrigation scheduling, soil moisture monitoring and fertigation. The fourth phase was the harvesting procedure. A suitable site for the trial was required before the first phase could commence.

3.1 Site Investigation and Selection

The following criteria were used in selecting a suitable site:

- the field must be available for use in the project;
- the field should be in a suitable climatic region for sugarcane growth;
- there should be an accessible and reliable water source; and
- the field must be near the Pietermaritzburg Campus of the University of KwaZulu-Natal and must be easily accessible for irrigation and testing purposes.

A field at the Ukulinga research farm met the above objectives and was selected for the trial. The soil types of the field were Westleigh and Mispah with a depth of 0.6 m (Moodley, 2001). Water was available from a hydrant on the North Western Side of the field shown in Figure 3.1. This, however, was the first time that sugarcane was planted at the farm. There is a weather station on the farm which supplied data for the *SAsched* irrigation scheduling tool (Lecler, 2004b). The Plots A to J were randomly assigned to ASFI plots and SSD irrigation plots in Section 3.3.1.

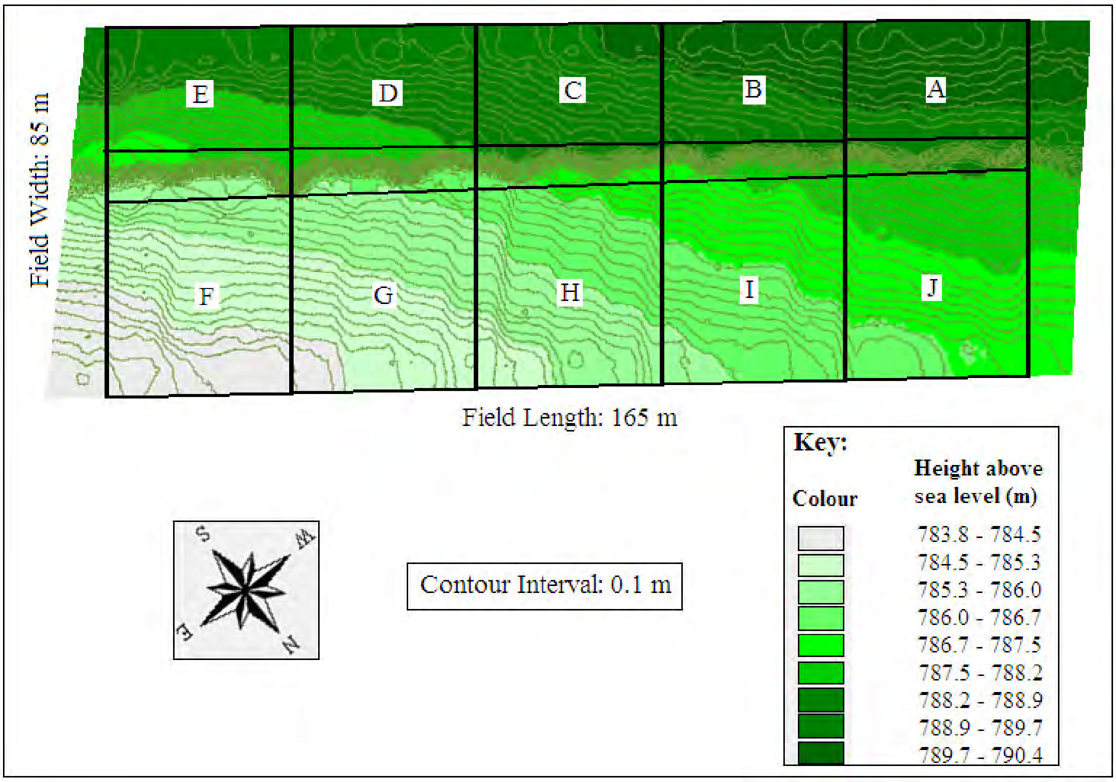

Figure 3.1 Contour map of selected field

3.2 ASFI Initial Development and Testing

The initial development and testing phase was an iterative process, undertaking both furrow tests and valve tests in parallel, to ensure that the valve meets the system requirements. Firstly, the system requirements were determined. Initial testing was then conducted at a field at the South African Sugarcane Research Institute (SASRI) in Mount Edgecombe to determine the optimum combination of variables, such as flow-rate and furrow slope, and to determine the pressure, flow and cut-off time requirements for the valve. The valve was then further developed to incorporate these requirements which led to the development of the final working prototype valve.

3.2.1 System requirements

The first step in developing the valve was to determine the system requirements. A robust, cost-effective valve was required to automatically control the direction of flow between the mainline and the lateral at set time intervals. This process is illustrated in Figure 3.2.

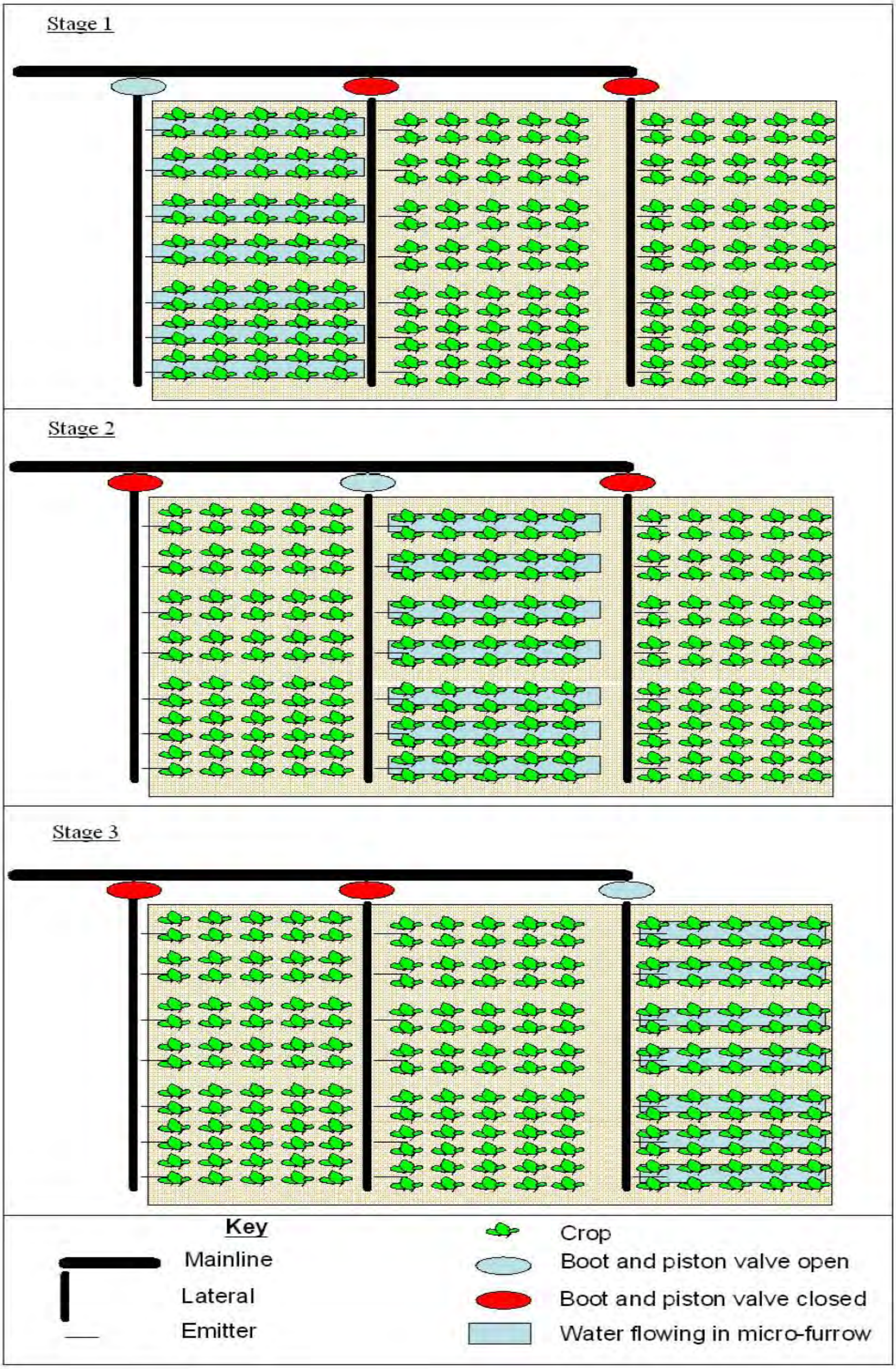

Figure 3.2 Stages of irrigating using the boot and piston valve (Lecler, 2006)

In Stage 1 of Figure 3.2, the first valve allows the water to flow down the first lateral. After the set time, the first valve closes the flow down the first lateral and directs the flow down the mainline, to the second valve. The second valve directs the flow down the second lateral as in Stage 2. The second valve will then shut off flow down the second lateral after the set time and direct the flow down the mainline to the next valve. This routine will continue to a number of further valves. The number of valves will depend on the total length of the field.

3.2.2 Preliminary field tests

An initial SFI test was conducted at SASRI, Mount Edgecombe. This was done to evaluate the performance of SFI and to gain a greater understanding of the characteristics of short furrows such as the wetting bulb and response to different inflow-rates. The furrows were tested to assess the optimum ranges and combinations of slope, flow-rate and irrigation time. The test furrow is shown in Figure 3.3.

Figure 3.3 Mount Edgecombe furrow after field test

The furrow length was set at 30 m. The results from the test were used in SIRMOD III to determine the robustness of ASFI. After simulating the tests in SIRMOD III, it was found that high *DUs* of 90 % to 100 % were possible for a wide range of combinations of flow-rates and application times for various slopes using 30 m furrows. However these results, although extremely uniform, might only be achieving an irrigation depth of 4 mm, for example, when a 10 mm irrigation depth was required. It was therefore decided to combine the *AE* and Requirement Efficiency (*RE*) to determine the optimum combinations of flow-rates and irrigation times and consequently a required irrigation depth was set. An irrigation application depth of 10 mm was selected as the required depth for this section.

The Combined Efficiency (CE) was calculated as in Equation 3.1

$$CE \quad = 0.4 \times DU + 0.3 \times AE + 0.3 \times RE \tag{3.1}$$

The CE is only meant as a guide and is not an accepted coefficient of performance or scientifically proven and was proposed during the Ukulinga field trial developments. The CE gives an indication of the optimum combination of flow-rate and irrigation time for a set irrigation depth. The AE and RE were given a lower factor of 0.3 as a result of these performance indicators being dependant on the selected irrigation depth. The selected irrigation depth is more of a management issue than a system variable. Numerous SIRMODIII simulations were conducted for each of the slopes in Figure 3.4 to assess which combination of variables would produce the highest CE. Once this was determined, variables such as flow-rate and cut-off time were then altered for a range of values, to assess the robustness of the system while keeping the other variable such as the soil infiltration characteristics from the Mount Edgecombe test furrow constant. Figure 3.4 illustrates the CE with varying the flow-rate and using a set irrigation time for various slopes. This was done to assess the impact of altering the flow-rate on the combined efficiency of the system. A high CE is possible for a range of combinations of flow-rates and irrigation times.

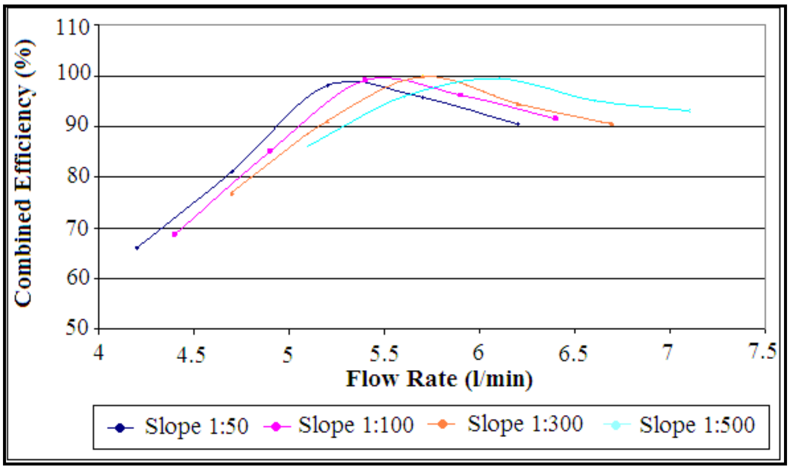

Figure 3.4 Combined Efficiency (CE) simulated with irrigation time kept constant and varying flow-rate with required depth equal to 10 mm

The effect of altering the irrigation time on CE is illustrated in Figure 3.5. Altering the irrigation time, by increasing or decreasing it by twenty minutes, still results in a highly efficient system for the range of slopes.

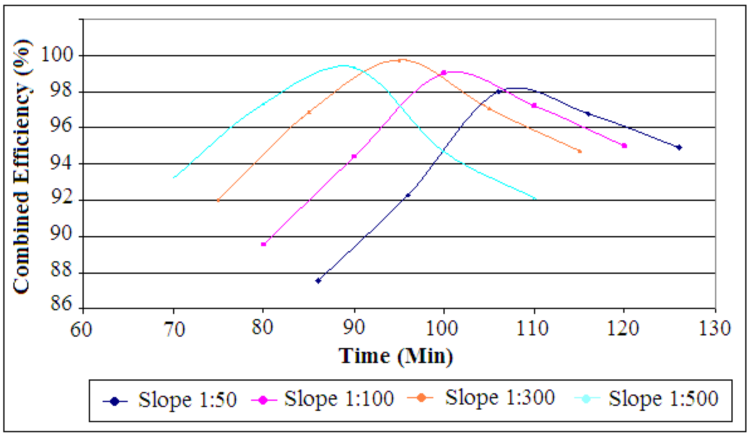

Figure 3.5 Combined Efficiency (*CE*) simulated for various slopes using optimum and set flow-rate for a required depth of 10 mm

The optimum *CE* was used to find the optimum combination of input variables. Figure 3.6 illustrates the robustness of ASFI on various slopes to a change in flow-rate from the optimum value (which is dependent on the localised, Mount Edgecombe, conditions) and the effect on the *DU*. The system performance is more susceptible to a flow-rate below optimum. This is verified by assessing the *CE* in Figure 3.4. A change in the optimum flow-rate of 1 l/min will still result in a *DU* of 88 % or higher for the various slopes. The flow-rate should therefore be set slightly above optimum to account for any errors. The steeper the slope, the more sensitive the system is to a decrease in flow-rate from the optimum value. However, when the flow-rate is altered above the optimum value, the various slopes all perform excellently. This shows that if the ASFI system is designed and set up correctly, a high *DU* is possible for a range of slopes, even taking variations in flow-rate into account.

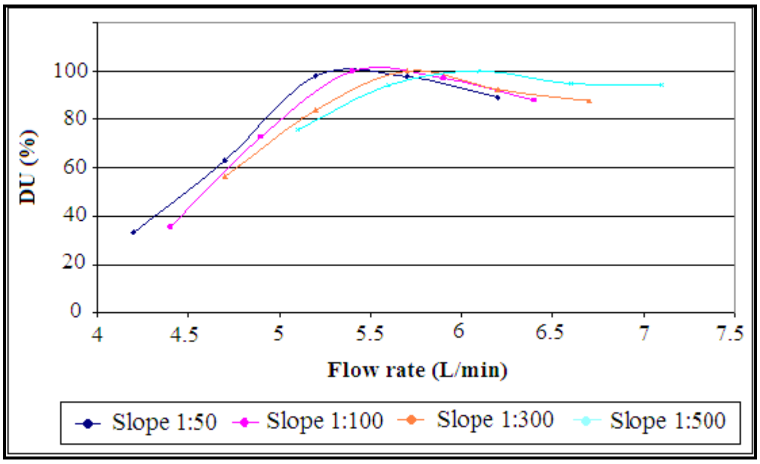

Figure 3.6 *DU* simulated with constant irrigation times and varying flow-rate for a required depth of 10 mm.

Altering the irrigation time from the optimum value does not significantly affect the *DU* of the system as shown in Figure 3.7. With irrigation times altered by 20 min on either side of the optimum irrigation time, the *DU* is still above 80 % for the range of slopes, illustrating the robustness of the ASFI system. The optimum irrigation time was between 90 and 110 minutes for this experiment, depending on the slopes. The steeper the slope, the greater the negative impact of altering the irrigation times. However, a slope of 1:50 still performs exceptionally well.

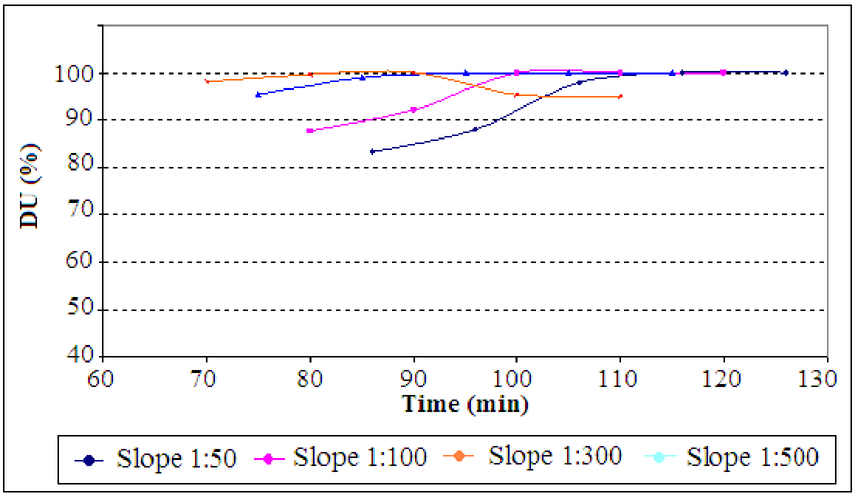

Figure 3.7 *DU* simulated for various slopes using a set flow-rate for a required depth of 10 mm

3.2.3 Development of a prototype valve

The focus of the valve development was to obtain a valve that could perform to the system requirements as stipulated in Section 3.2.1. The optimum combination of input parameters, obtained in Section 3.2.2, are based on the localised soil conditions such as soil type but were still suitable to be used as guidelines as to the cut-off time and flow requirements for the Ukulinga prototype valve. The piston valve, shown in Figure 3.8, was recommended by Jumman and Mills (2005) as introduced in Section 2.3.2 and was selected as the valve that would be further developed for use in the Ukulinga trial.

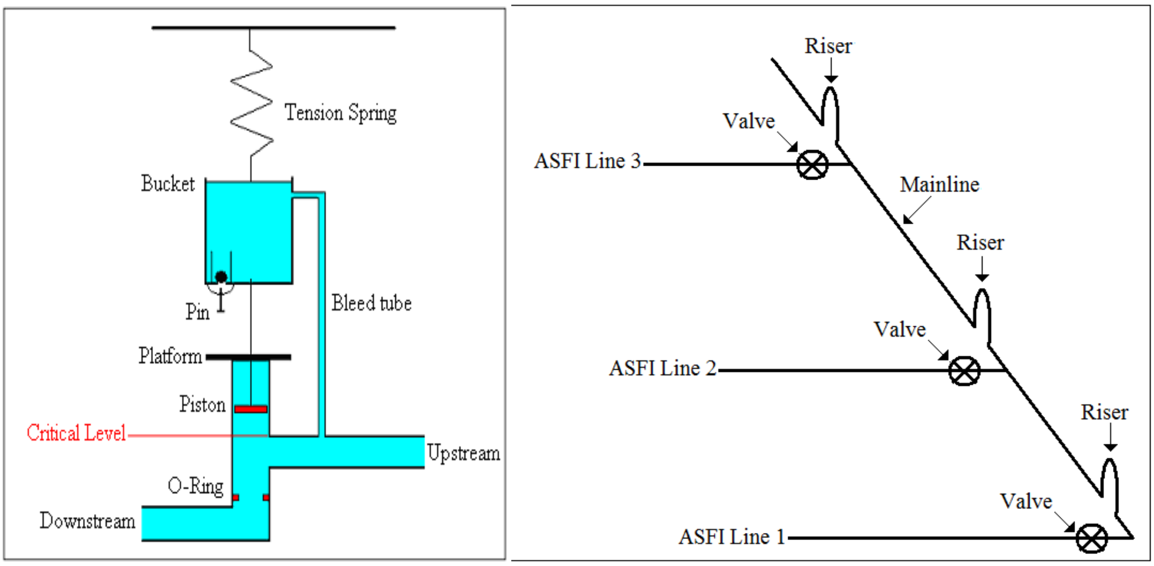

Figure 3.8 Diagram of the Piston Valve (Jumman and Mills, 2005) and location of the valve in the system

The piston valve shown in Figure 3.8 still had a number of problems. Firstly, this valve was not able to eliminate the need for a riser. The riser used the difference between static and dynamic head, generally between 3 and 5 cm, to control flow between the various plots. The riser therefore needed to be accurately positioned and slight variations in the system inlet pressure would cause the system to stop working. Also, if the head in the mainline was 5 m, the riser would need to be 5 m tall. The second problem with the valve was the bucket. The first problem with the bucket was sealing the container, with the pin and ball resulting in leaks. The second problem with the bucket was that the greater the pressure in the system, the larger the bucket needed to be. The bucket in Figure 3.8 was only suitable for a pressure of up to about 0.8 m. The spring was the third problem, but it was envisaged that this would be overcome by using a compression spring, making the whole system more compact.

A theoretic analysis of the furrow test results obtained from the tests conducted at Mount Edgecombe, resulted in a practical system layout with indications as to the pressure, flow-rate and cut-off requirements of the valve. The development of the prototype valve required the consideration of these factors as well as eliminating the problems associated with the piston valve. A number of developments were tested using a valve testing rig which consisted of a supply tank at 4.5 m above the valve. A hydrant was used to fill the tank and to match the flow-rate leaving the tank via LDPE pipe to the valve. The valve used for the Ukulinga trial should be able to direct the supplied water down the lateral and then, after a set time period, direct the water down the sub-main to the next valve, eliminating the need for the riser. A number of options were developed and tested leading to the development of the prototype valve used in the Ukulinga trial.

These developmental valves led to the concept of the boot and piston valve, shown in Figure 3.9. The valve was tested and was able to operate under various inlet pressures using the test rig. However, there were a number of problems with the test rig. The supply pressure from the test rig tank varied, it was difficult to replicate practical downstream flow and pressure requirements and it was difficult to move the supply tank to obtain different supply pressures. It was decided that comprehensive valve tests would take place while the valve was in use in the field where the supply head was more controlled and consistent.

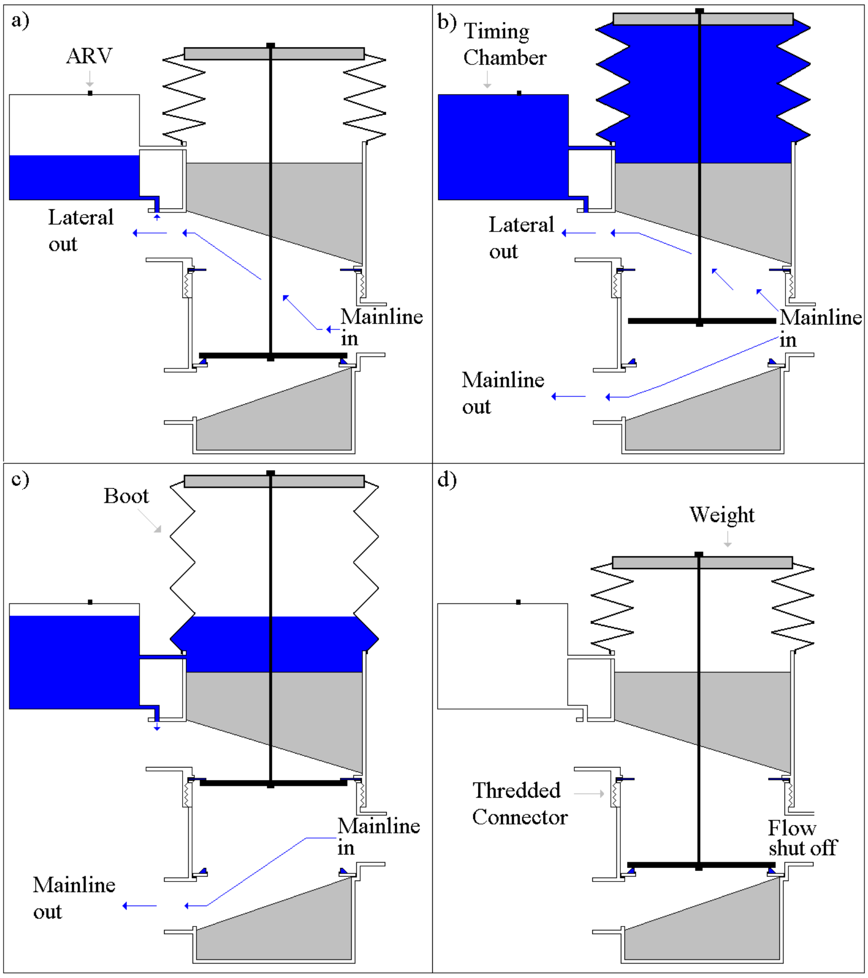

Figure 3.9 Boot and Piston valve at various stages of valve opening and closing with a) flow out the lateral, b) the valve starting to shut, c) the flow continuing along the mainline and d) flow into the system shut

The boot piston valve works as follows: water flows into the valve via the mainline and is prevented from continuing down the mainline due to the piston. The water is therefore diverted down the lateral, as illustrated in Figure 3.9a. A bleed tube off the lateral is used to fill a timing chamber. The timing chamber is used to achieve the required cut-off time. When the timing chamber is full, the Air Release Valve (ARV) shuts and water bleeds into the expandable boot. When the pressure in the expandable boot has increased sufficiently to overcome the downward pressure on the piston, the valve begins to open. This is possible due to the surface area of the boot being larger than the surface area of the piston, therefore resulting in a larger upward force. Water is then able to flow under the piston as in Figure 3.9b. The pressure on the bottom the piston will increase to the same as the pressure on the top of the piston. Therefore, the valve piston moves up quickly due to the pressure in the expandable boot, and shuts off the flow in the lateral. The time taken between the outlet of the mainline being totally shut, as in Figure 3.9a, and the "lateral out" being totally shut, as in Figure 3.9c, is approximately 1 second. This is a suitable shut off time. If the shut off was quicker, there would be water hammer in the system which could cause pipes or the valve to burst. If the shut off time was slower, it would affect the performance of the system as it would result in two laterals being irrigated simultaneously.

Once the valve shuts off the flow in the lateral, the water in the expandable boot and timing chamber drains down the lateral. However, the pressure in the valve enables the valve to stay open with the piston in the top position, as shown in Figure 3.9c. The bleed tube being connected to the lateral results in only a small time period when the boot is pressurised. This greatly reduces wear on the boot. Once the piston moves up, the water continues down the mainline to the second valve on the mainline where the above process is repeated. This continues up to the last valve which is represented in Figure 3.9d. When the end valve shuts off, water in the system stops with the pressure in the system keeping the valve in the upward position. When the main valve for the block or the pump is turned off, the pressure in the system decreases and the valves reset to the downward position due to the weight on the top of the valve.

Valve development was continued during the Ukulinga field trial by assessing the valve's shortcomings and implementing the necessary improvements. A photo of the final valve used in the Ukulinga trial is shown in Figure 3.10. The valve is made from "off the shelf" parts. The size of the valve is limited by the available rubber boot size. The hydromatic fittings are used for the valve pressure tests in Section 4.1. The hydromatic fittings have the additional advantage of acting as air release valves.

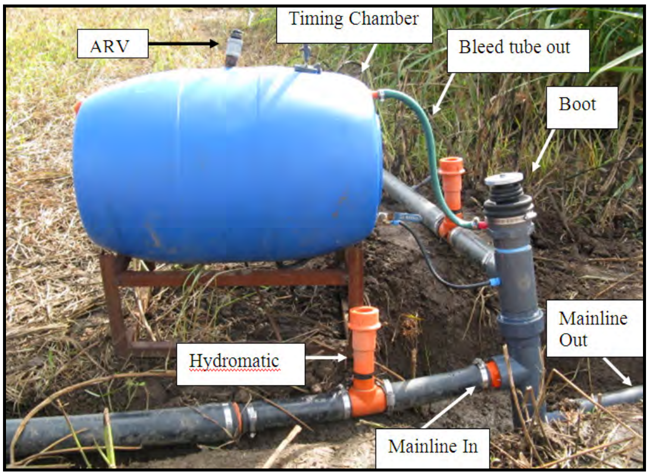

Figure 3.10 In-field Boot and Piston valve

For practical reasons, a 50 litre container was set as the maximum timing chamber capacity. Due to leaks through the ARV, a minimum inflow-rate into the timing chamber of 1.25 l/min was required to create sufficient pressure in the timing chamber for the ARV to seal and pressurise the system. A maximum irrigation time of 42 minutes was therefore selected which was significantly less than the 90 to 110 minutes obtained from the optimisation of the Mount Edgecombe test results. High *DUs* and a robust system is still theoretically possible for a shorter irrigation time by increasing the flow-rate, as discussed when assessing the robustness of the ASFI system for large-scale application in Sections 5.1 to 5.3. The leaks through the ARV could be reduced with further development of the ARV.

Tests at the hydrant revealed a system delivery flow-rate of 4.67 l/s. The width of the field, excluding the contour bank, was approximately 45 m. At a furrow spacing of 1.8 m, there would be 24 emitters which resulted in a maximum emitter flow-rate of 11.68 l/min.

There was only one occasion when the valve malfunctioned during usage at the Ukulinga trial. This was due to the original bleed tube from the timing chamber to the rubber boot being too small. When the valve started to open, the flow of water through the bleed tube was inadequate to maintain the pressure required in the rubber boot, for the valve to open fully. A larger bleed tube, as shown in Figure 3.10, was then installed which rectified the problem.

3.3 Trial Establishment

The trial establishment involved setting up the trial site so that each system could be evaluated and their performance compared. This included the ASFI and SSD irrigation designs, land preparation, planting and irrigation installation.

3.3.1 ASFI design

The first step in the ASFI design was to construct a test furrow in a field adjacent to the experimental plot. This was done to assess how the localised conditions such as soil type would respond to an irrigation event. Pegs were placed at 5 m intervals along the furrow. A dumpy level was used to determine the slope of the test furrow with the average slope being 1:40 (or 2.15 %). A blocked-end furrow was used. A number of irrigation runs were conducted on the test furrow to enable the test furrow to stabilise over time, due to the furrow being smoothed out, with fewer obstructions, and the watercourse being more defined. This accounts for the advance front becoming quicker with each irrigation event until the furrow stabilises. The advance front time will then stabilise and be relatively constant for each irrigation event depending on the soil moisture content. Once the test furrow had stabilised, tests were conducted on the advance and recession fronts. These results are recorded in Table 3.1.

Table 3.1 Recorded advance and recession front for the Ukulinga test furrow

Distance (m)	Advance Time (min:sec)	Recession Time (min:sec)
5	1:48	37:20
10	4:09	37:42
15	7:12	38:06
20	11:17	39:27
25	20:32	45:15
30	31.05	51:52

The cut-off time of 42 minutes and flow-rate of 11.68 l/min were not used due to the furrow being steep (1:40) and a cut-off time of 35 minutes and flow-rate of 10 l/min were selected for the test furrow. For this test a gross irrigation requirement per day of 3 mm was assumed, resulting in a required application depth of 6 mm, with an irrigation event happening every second day during peak demand months. The above recordings were input to SIRMOD III to simulate the furrow performance of the irrigation event. The “two-point compute infiltration function” in SIRMOD III, which utilises the advance time at two selected points along the furrow to simulate the advance and recession fronts for the furrow, was then run. An abbreviated output from the simulated results is recorded in Table 3.2. There are discrepancies between the measured results in Table 3.1 and the simulated results in Table 3.2.

Table 3.2 Advance and recession front simulated by SIRMOD III with system generated Kostiakov a and K values

Distance (m)	**Advance Time (min:sec)**	**Recession Time (min:sec)**
0	0:00	37:30
5	1:25	37:30
10	3:50	37:30
15	7:53	37:30
20	12:56	38:24
25	18:04	39:00
30	29:48	54:14

Slight adjustments to input parameters, *a* and *K* parameters in the Kostiakov equation, were made to obtain a better match between the simulated and measured results. When comparing the results with the modified Kostiakov *a* and *K* values in Table 3.3 to the recorded values in Table 3.1, there is an almost identical advance front. However, the recession front does vary slightly. A perfect fit of the recession front is unlikely as it is difficult to identify the exact time that a recession front passes past a specific point.

Table 3.3 Advance and recession front output from SIRMOD III with modified Kostiakov a and K values.

Distance (m)	**Advance Time (min:sec)**	**Recession Time (min:sec)**
0	0:00	38:00
5	1:46	38:00
10	3:58	38:00
15	7:09	38:00
20	12:01	38:00
25	19:51	38:00
30	30:59	49:66

The variables that were used for the Ukulinga test furrow, including the irrigation time, flow-rate and furrow slope and shape, were used in SIRMOD III to determine theoretical performance indicators. According to results from the SIRMOD III simulations, the irrigation event produced a *DU* of 72 %, an *AE* of 88.5 % and a *RE* of 93 %. To optimise the results using the Ukulinga soil conditions, it is recommended that a higher flow-rate and flatter slopes of approximately 1:250 (0.4 %) should be used. The higher flow-rate would result in the water moving down the furrow faster, which in this case would result in a better *DU*. Figure 3.11, Figure 3.12 and Figure 3.13 are surface and subsurface flow profiles at various stages of the irrigation event. Figure 3.11 represents the profile with the advance front at 15 m. In Figure 3.12, the water has reached the end of the furrow and starts to pond, with the recession front approaching the end of the furrow. It would be at this stage that the inflow into the furrow is shut off. Figure 3.13 is of the final soil water distribution.

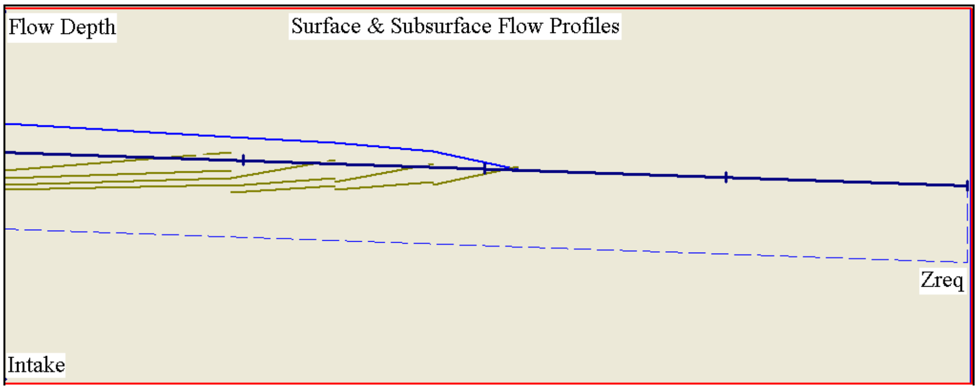

Figure 3.11 Surface and subsurface flow profile at 15 m for the Ukulinga test furrow

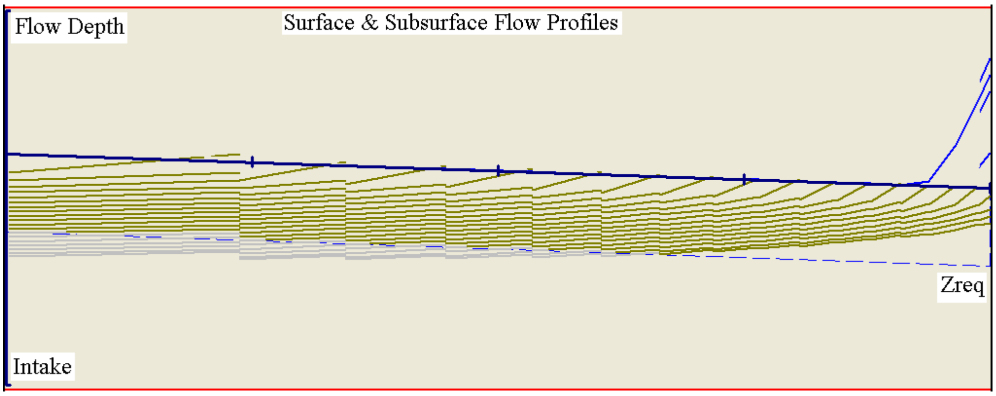

Figure 3.12 Surface and subsurface flow profile at furrow end for the Ukulinga test furrow

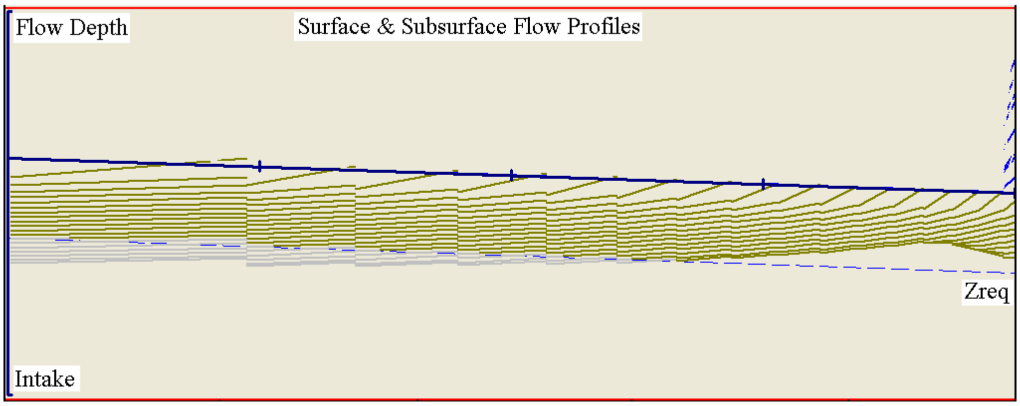

Figure 3.13 Surface and subsurface flow profile at irrigation completion for the Ukulinga test furrow

The next part of the design was to determine the layout of the trial. The Ukulinga trial site was split into 10 plots, each 30 m long. The plots were then randomly divided, with plots B, D, G, I and J as the ASFI plots and plots A, C, E, F and H as the drip irrigation plots, as shown in Figure 3.14. Plots A and J were later removed due to the gap filling described in Chapter 3.3.5, which impacted the randomness of the plot selection. Note: Figure 3.14 will be referred to and used during the remainder of the chapter.

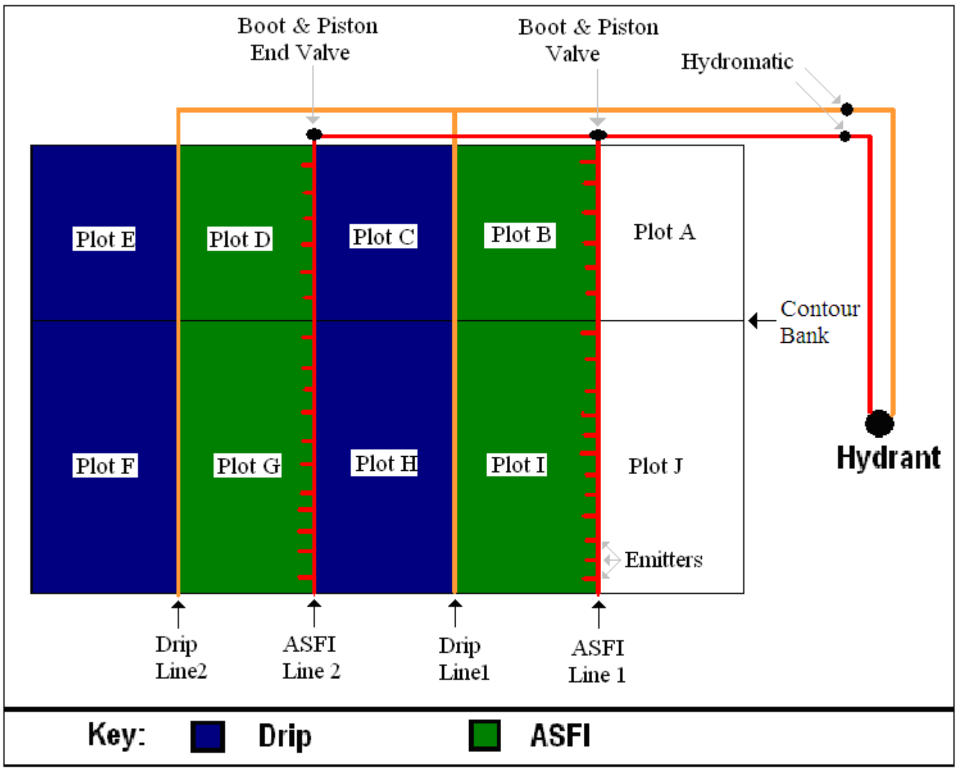

Figure 3.14 Field layout with randomly selected plots

The field was surveyed using a Trimble Asset Surveyor v5.00 TSC1 GPS with the resultant contour map shown in Figure 3.1. The contour bank was used as the division between the top half and bottom half of the field in Figure 3.14. The field area was then analysed. It was decided to divide the field into 30 m long sections with a 2 m gap between each section, with pegs placed at the corners of each section as well as at 10 m intervals across the field. These points were then surveyed with a dumpy level. The survey results were then used to design the drip irrigation and ASFI laterals and mainlines.

Once the trial layout was finalised, the ASFI design could commence. The first step was to determine the gross irrigation requirement. The rainfall and reference A-pan evaporation for Ukulinga, was used to determine the monthly nett irrigation requirement (NIR). The peak NIR was for August with a monthly NIR of 78.4 mm, as in Table 3.4. However, this procedure assumes that all the rainfall is effective. Preliminary simulations using SA*sched* revealed that in order to take effective rainfall into account, a safety factor of 1.2 was used, resulting in a NIR = 94.1 mm for the month of August.

Table 3.4 Rainfall and reference evaporation data for Ukulinga

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rainfall (mm/month)	91	92	89	39	19	11	9	25	57	88	101	98
Reference Evap. (mm/day)	4.6	4.4	3.8	3.1	2.5	2.3	2.4	2.9	3.6	3.9	4.4	4.5
Reference Evap. (mm/month)	142.6	123.2	117.8	93	77.5	69	74.4	89.9	108	120.9	132	139.5
Crop ET (mm/ month) (crop factor of 1.15)	164.0	141.7	135.5	107	89.1	79.4	85.6	103.4	124	139	151.8	160.4
NIR (mm)	73	49.7	46.5	68	70.1	68.4	76.6	**78.4**	67	51	50.8	62.4

The soil profile for the field is given in Table 3.5 and soil water content in Table 3.6.

Table 3.5 Soil profile characteristics (Moodley, 2001)

Horizon	**Depth (m)**	**Description**
A	0 – 0.26	Very dark brown, silty clay loam, hard when dry
B	0.26 – 0.55	Dark reddish grey, gravely silty clay loam

Table 3.6 Soil water content (Moodley, 2001)

Horizon	**Depth** (m)	**Wilting Point (WP)** (mm/m)	**Field Capacity (FC)** (mm/m)	**Soil Water Capacity (SWC)** (mm/m)
A	0.26	112	213	101
B	0.29	158	277	119

The available water (AW) was calculated as follows:

$$\begin{aligned} AW &= SWC \times ERD \qquad (3.2) \\ &= (101 \times 0.26) + (119 \times 0.29) \\ &= 60.77 \text{ mm} \end{aligned}$$

where: SWC = Soil Water Capacity, and

ERD = The effective rooting depth (mm) (ARC, 2003)

The readily available water (RAW) was calculated using an allowable water depletion of 20 % and not approximately 50 % (which common for sugar cane) due to the frequent applications used for ASFI :

$$\begin{aligned} RAW &= AW \times \text{allowable water depletion} \qquad (3.3) \\ &= 60.77 \times 0.2 \\ &= 12.154 \text{ mm} \end{aligned}$$

The nett irrigation requirement per day (NIR_d) was calculated as follows:

$$\begin{aligned} NIR_d &= NIR \,/\, \text{days in a month} \qquad (3.4) \\ &= 94.1 / 31 \\ &= 3.0 \text{ mm/day} \end{aligned}$$

A wetted width over the 1.8 m spacing of 65 cm was assumed, resulting in the wetted area as a percentage, W, of 36 %. The cycle time, t_c, was calculated as follows:

$$\begin{aligned} t_c &= (RAW / NIR_d) \times (W / 100) \qquad (3.5) \\ &= (12.154 / 3.0) \times (36 / 100) \\ &= 1.5 \text{ days} \end{aligned}$$

However, a t_c of 1.5 would result in an application depth of 4.5 mm which may increase evaporation from the soil. A t_c of 3 days was selected.

The Nett Irrigation Requirement per cycle (NIR_c) is therefore:

$$\begin{aligned} NIR_c &= NIR_d \times t_c \\ &= 3 \times 3 \\ &= 9 \text{ mm} \end{aligned} \tag{3.6}$$

The Gross Irrigation Requirement per cycle (GIR_c) is therefore:

$$\begin{aligned} GIR_c &= NIR_c \times (100/\eta) \\ &= 9 / 0.95 \\ &= 9.5 \text{ mm} \end{aligned} \tag{3.7}$$

where: η = system efficiency (%)

An application depth of 6 mm was used for the test furrow previously in this section due to the steep slopes. However, according to SIRMOD III simulations, an application depth of 9.5 mm is possible for a furrow slope of 1:250, a furrow inflow-rate of 11.25 l/min and a cut-off time of 42 minutes. Applying an irrigation depth of 9.5 mm instead of 6 mm would hopefully reduce evaporation losses. The ASFI system was then designed with the mainline along the top of the field (as in Figure 3.14), with the lateral running perpendicular to the mainline, down the slope. The friction losses associated with decreasing the pipe size down the lateral is used to negate the head gain due to the slope of the lateral. The detailed ASFI lateral design is in the accompanying CD as an excel spreadsheet named “ASFI_design”. The lateral was designed using a spreadsheet based on the Hazen-Williams formula, as discussed in ARC (2003). This resulted in the total flow-rate required for the lateral being 16.2 m^3/hr.

The next step in the design was to determine the pressure losses in each section of the mainline using a systematic process from the furthest point on the mainline pipes to the hydrant. For the mainline design between ASFI Lines 2 and 1 (as illustrated in Figure 3.14), it was important to minimise pressure supply differences between the two laterals. However, LDPE pipe sizes larger than 65 mm were hard to source. Hence, two 65 mm LDPE pipes were connected in parallel, to reduce the head losses in the pipe. The design procedure and equations used were obtained from ARC (2003).

$$h_f = 4.516 \times 10^{-10} \times l \times Q^{1.77} / d_i^{4.77} \tag{3.8}$$
$$= 4.516 \times 10^{-10} \times (64) \times (16.2/2)^{1.77} / 0.065^{4.77}$$
$$= 0.54 \text{ m}$$

where: h_f = friction loss in the pipe (m),

l = pipe length (m),

Q = Flow-rate in the pipe (m^3/hr), and

d_i = the internal pipe diameter (m).

$$h_{valve} = \text{number of bends} \times k \times v^2 / 2g \tag{3.9}$$
$$= 6 \times 0.75 \times 1.356^2 / (2 \times 9.81)$$
$$= 0.42 \text{ m}$$

where: k = friction co-efficient through the valve (from ARC, 2003), and

v = velocity of water in pipe (m/s).

$$h_{L1} = h_{L2} + h_s + h_f + h_{valve} \tag{3.10}$$
$$= 5.00 - 0.78 + 0.54 + 0.42$$
$$= 5.18 \text{ m}$$

where: h_{L1} = head at point where Lateral 1 meets the mainline (m),

h_{L2} = head at point where Lateral 2 meets the mainline (m), and

h_s = head difference due to the field slope (m).

For the mainline design between Lateral 1 and the hydrant, pressure losses were not a problem as the supply pressure to the system was significantly larger than required. The mainline between the hydrant and Lateral 1 was therefore used to reduce the pressure at the lateral connection points to approximately 5 m.

There was, previously, a Lateral 0 feeding Plot A, in Figure 3.14, which was the plot that was removed for gap filling. Below is the main line design between Lateral 1 and the position where Lateral 0 was connected (using 65 mm LDPE pipe):

$$h_f = 4.516 \times 10^{-10} \times l \times Q^{1.77} / d_i^{4.77} \tag{3.11}$$
$$= 4.516 \times 10^{-10} \times (2) \times 16.2^{1.77} / 0.065^{4.77}$$
$$= 0.06 \text{ m}$$

$$h_{valve2} = \text{number of bends} \times k \times v^2 / 2g \tag{3.12}$$

$$= 6\times0.75\times1.356^2/2\times9.81$$

$$= 0.42$$

$$h_{L0} = h_{L1} + \mathrm{h_s} + h_f + h_{valve} \quad (3.13)$$

$$= 5.18 + 0 + 0.06 + 0.42$$

$$= 5.66 \text{ m}$$

where: h_{L0} = Head at previous connection point of Lateral 0 to the mainline (m),

The mainline was then designed from the previous position of Lateral 0 would have been to the hydrant. A pressure at the hydrant of approximately 16 m was required to match the designed pressure of the SSD system at the hydrant, so that either the SSD or ASFI systems would run optimally when the respective ball valve was fully opened. The height of original connection point of Lateral 0 was 2.45 m above the hydrant. The pipe length between the hydrant and the lateral was 75.8 m.

$$h_{valve1} = \text{number of bends} \times k \times v^2 / 2g \quad (3.14)$$

$$= 5\times0.75\times1.356^2/2\times9.81$$

$$= 0.35$$

$$H_{hydrant} = h_{L0} + h_s + h_f + \text{valve losses} \quad (3.15)$$

$$16 = 5.66 + 2.05 + \mathrm{h_f} + 0.35$$

$$h_f = 7.94$$

The equation ($h_f = 4.516\times10^{-10} \times l \times Q^{1.77} / d_i^{4.77}$) was used to match the pressure at the hydrant for the ASFI system to the pressure at the hydrant for the drip system. This resulted in 74 m of 50 mm LDPE and 1.8 m of 40 mm for the mainline between the existing connection point of Lateral 0 and the hydrant.

3.3.2 Drip irrigation design

Upon analysing the results from the GPS and dumpy level survey, it was decided to run the drip irrigation mainline along the top of the field. The mainline was not run along the contour bank down the centre of the field as this was approximately 2 m lower than the top of the field, which would result in poor uniformities. The lateral pipe size was decreased down the lateral so that frictional losses counteracted the height difference, resulting in consistent pressures down the mainline. The drip irrigation line 1 and 2 design spreadsheet is on the accompanying CD as an excel spreadsheet named “Drip_design”. The drip design is included in APPENDIX A as the focus of this report is on the ASFI system.

3.3.3 Land preparation

While the systems were being designed, the initial stages of the land preparation commenced. Ideally, ASFI should be a no till system once the field has been initially levelled. The Ukulinga trial plot was fallow land, and it was therefore necessary to till the land to remove weeds. A deep ripper, a plough and then a disk were used to prepare the soil. Ideally, the field should be laser levelled/smoothed using a leveller or grader. However, the plot was far away from conventional surface irrigation areas, so a laser leveller could not be used. All contract graders in the area were unavailable for use at the required time. A land plane which was towed behind a tractor was therefore used to smooth the field, rather than level the surface. Plot G was not smoothed to assess the impact of such a practise on irrigation performance and therefore yield. Using a land plane instead of a grader/leveller resulted in the slope along the length of the field being approximately 1:40, significantly steeper than the required value of 1:250 for the furrow slope. The furrows were therefore pegged along the contour to obtain a slope of 1:250. However, this resulted in an impractical layout with a large variation in furrow lengths along the lateral. This was due to the layout of the trial site. The contour banks above the field, along the middle of the field and below the field were not along the contour, but directly along the length of the field. It was therefore decided to construct the furrows along the length of the field.

3.3.4 Furrow shaper

The next step in the Ukulinga trial establishment was to develop an implement that could be used to construct a smooth irrigation furrow between the two planting furrows. The irrigation furrow dimensions for this trial was approximately 30 cm to 40 cm wide at the top, and 15 cm to 20 cm deep. The irrigation furrow needs to have a consistent depth and be as smooth as possible with minimal obstructions to ensure improved *DU*s. A number of tests were conducted on prototype furrow shapers in the development of the furrow shaper as illustrated in Figure 3.15. Firstly, the furrow shaper was tested with only the ridger. However, once the ridger had passed through the soil, some of the soil clods tended to fall back into the furrow. The curved pipe with a motorbike rear shock absorber was then added to the back of the furrow to break down these clods and smooth the furrows. The design for the furrow shaper is not optimal as some clods fell in behind the furrow shaper and the curved pipe was not able to compress all the clods. However, optimising the furrow shaper is beyond the scope of this project.

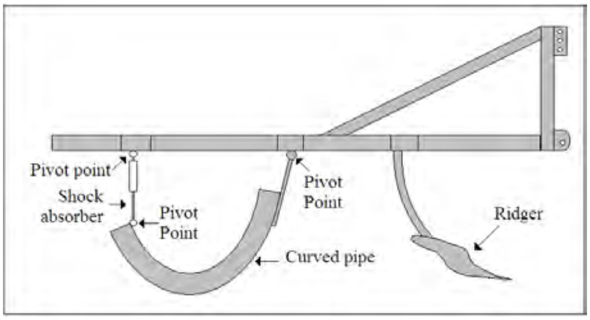

Figure 3.15 Furrow shaper

3.3.5 Planting and furrow shaping

The planting operation took place on the 8th and 9th of March 2007. The seed cane was planted along the length of the field, with a slope of approximately 1:40. Two one-sided ridgers (pigs ears) were used to create the planting furrows at a spacing of 60 cm. The reason that one-sided ridgers were used was to throw the soil in one direction. The seed cane would then be easier to cover. Once the tractor had turned at the end of the field, the one tractor wheel was positioned along the path of its previous trip, resulting in a furrow spacing of 1.8 m. The variety of sugarcane planted was N31. Details on this variety can be found in Anon (2005). The seed cane was covered using a hoe, as shown if Figure 3.16.

Figure 3.16 Seed cane in furrows and being covered using a hoe

Soil samples were taken at ten random positions in the field. The samples were taken to a soils laboratory and analysed. From the analysis, it was decided to apply single super phosphate in furrow before planting to meet the phosphorus requirements. The fertiliser requirement calculations are shown in Table 3.7.

Table 3.7 Calculations of fertiliser required

Nutrient	**Requirement (kg/ha)**			
P	70	Phosphorus		
N	140	Nitrogen		
K	180	Potassium		
		Amount		**Calculations**
Single supers contains:		10.50 %	P	
Spacing:		1.8	M	
No. of planting lines in 1.8 m spacing:		2		
Running m for 1 ha:		11111.1	M	(=10000 x 2/1.8)
Trial Area:		7350	m^2	
Therefore running m for trial area:		8166.67	M	(=11111.11 x 7350/10000)
kg P per m in planting furrow:		0.0063	kg/m	(=70/11111.11)
kg single supers per m in furrow:		0.06	kg/m	(=0.0063/0.105)
Total single super requirements:		490	kg/m	(=0.06 x 8166.667)

The fertiliser applicator, as shown in Figure 3.17, was adjusted to obtain a flow-rate of 0.06 kg/m. This was checked by filling the applicator with a set weight of fertiliser, walking a set distance, and then reweighing the contents. The weight difference was then divided by the distance travelled, confirming the 0.06 kg/m flow-rate. The applicator was then moved into the field, where the applicator was run in the planting furrow along the length of the field.

Figure 3.17 Fertiliser Application

The seed cane was then placed in the planting furrows, cut and covered. The furrow shaper was then used to construct the irrigation furrow between the two rows of seed cane as in Figure 3.18. This proved to be problematic as it was difficult to locate the planted furrow. This problem was compounded by the fact that the seed cane was frequently cut longer than the 30 cm to 40 cm sections that were required. The majority of the seed cane that was removed while constructing the irrigation furrow consisted of longer stalks that had not been cut into smaller billets. Once the irrigation furrows were installed, the furrows were inspected and obstructions removed. The ends of the irrigation furrows were then blocked.

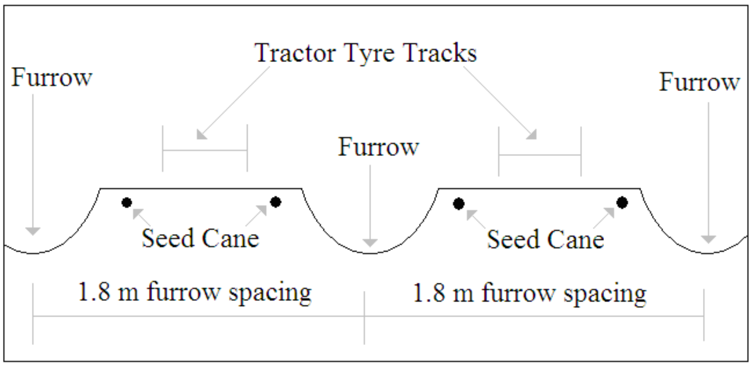

Figure 3.18 Planting configuration

When assessing the planting and furrow shaping procedure used, an improved planting procedure was identified. The seed cane could be cut into short sections prior to placing it in the furrow. The seed cane would then be placed in the furrow and not covered. The irrigation furrow would then be shaped between the easily visible planting furrows, which would eliminate the seed cane being removed during furrow construction. If the seed cane is removed, this could simply be replaced in the planting furrow. While shaping the irrigation furrow, the soil from the irrigation furrow will be pushed over the planting furrow, assisting in the covering operation.

As a result of the problems encountered during planting, gap filling was required. Gap filling took place at a later stage on the 10th to the 11th of May 2007, once the sugarcane shoots were between 10 cm to 20 cm high. The areas that required gap filling were measured and were then assessed to see whether the problem was due to poor germination or mechanical problems. In Plot B to Plot E in the top half of the field, approximately 20 % of the area required gap filling. It was estimated that 10 % was due to poor germination as a result of the long seed cane stalks and 10 % was as a result of the seed cane being removed by the furrow shaper. Plot F to Plot G had approximately 25 % of the area requiring gap filling with 10 % due to poor germination and 15 % due to the furrow shaper removing the seed cane.

3.3.6 Furrow slope survey

Once the irrigation furrows were constructed, as described in Chapter 3.3.5, the furrows were surveyed. This was done using a dumpy level and tape measure, with the staff placed at 10 m intervals within the furrow. The results from the survey are recorded in Table 3.8. The average furrow slope was 1:40, significantly steeper than the designed slope of 1:250, which results in a quicker advance front along the furrows and ponding at the end of the furrow.

As a result of Plot G (illustrated in Figure 3.14) being left unlevelled, a number of furrows appeared to have a ridge perpendicular to the furrow at approximately 5 m from the start of the furrow. The dumpy level and staff were used to assess the slope of this section at approximately 30 cm intervals between the start of the furrow and the 10 m. Although the furrow slope was not uniform, the furrow sloped downhill along the entire furrow. In this notation, the letters (e.g. B) references the plot as in Figure 3.14 and the number, depicts the location of the furrow with reference to the top of the plot. For example, B5 represents the fifth furrow from the top of plot B.

Table 3.8 Furrow slopes for ASFI laterals 1 and 2

Line 1				**Line 2**		
Plot	**Furrow Number**	**Slope**		**Plot**	**Furrow Number**	**Slope**
B	2	01:39.5		D	2	01:42.9
B	4	01:39.0		D	4	01:43.5
B	5	01:42.3		D	6	01:35.7
B	6	01:39.5				
I	2	01:46.2		G	2	01:40.5
I	4	01:38.5		G	4	01:39.5
I	6	01:38.0		G	6	01:35.7
I	8	01:37.5		G	8	01:34.5
I	10	01:40.5		G	10	01:31.6
I	12	01:40.0		G	12	01:29.1
I	14	01:41.1		G	14	01:29.1
I	16	01:39.5		G	16	01:28.8

3.3.7 Irrigation installation

Once the furrows were shaped, the drip irrigation and ASFI systems were installed as per design. The drip tape was laid, as in Figure 3.19a, at a depth of 150 mm (the same depth as the furrows) and covered. The start of the ASFI and drip mainlines were then each connected to a water meter and a ball valve. The two lines were then connected together using a tee-piece as shown at the left of Figure 3.19b. The hydrant, pressure regulating valve, venturi and disk filter were then installed as shown in Figure 3.19b.

Figure 3.19 a) Drip tape installation b) Hydrant fittings

Once both irrigation systems were connected, the SSD irrigation system was then turned on. The pressure regulating valve was then adjusted so that the pressure in the system was according to the design. The pressures were checked at the hydromatic (position illustrated in Figure 3.14). The SSD system was then turned off and the ASFI system turned on. The pressure was evaluated at various points along the system to check if pressures corresponded with the designed values, including points just before and just after the boot and piston valve. The results from the pressure test on the valve are recorded in Chapter 4.1. The flow-rates for three emitters on each lateral were then measured, with an average flow-rate of 11.5 l/min.

Once the furrows were starting to equilibrate, with irrigation advance times becoming more consistent for each irrigation event, the ASFI system was evaluated to ensure that the performance of each emitter and furrow was satisfactory. To assess the emitter and furrow performance, the advance time to the end of the furrow was recorded on 24 May 2007 for each of the furrows. These results are recorded in APPENDIX B which also included a performance analysis of each furrow. These were not meant to be ASFI performance tests (these are included in Chapter 4.2), but were meant to identify and eliminate problems. The test was the tenth irrigation event of the year. The soil moisture was at 2.3 mm above the soil Drained Upper Limit (*DUL*), according to *SASched* (discussed in Section 3.4.1), which resulted in the quickening of irrigation advance time for the furrows. The soil moisture was above the *DUL*, not 20-30 mm below the *DUL,* as discussed in Section 3.4.1, due to a large number of irrigation events that were applied to smooth out the newly constructed furrow. The major problem was the quick irrigation advance rates which were due to the steep slopes of 1:40. However, it was also noted that the kinetic energy of the water from the emitter resulted in a quicker advance front and erosion near the start of each furrow. It was therefore decided to place the end of the emitter pipe into a short section of PVC pipe to dissipate the kinetic energy. This rectified the majority of the problems, but is not a substitute for a properly installed system with a slope of approximately 1:250, as per designed. Other smaller issues were corrected by removing obstructions and smoothing out the furrow.

The pressure at the end of each of the dripper lines was recorded shortly after the irrigation installation to ensure that the system was installed correctly with no blockages. For drip irrigation Lines 1 and 2 (as illustrated in Figure 4.1), pressures at the end of the dripper line (or laterals) varied between 10 m and 12 m with a maximum percentage variation of 9.9 % and 10 % from the average value of 10.92 m and 10.91 m respectively. Although the pressure was slightly higher than the designed value of 10 m, this does not have a significant impact on the flow-rate through each drip emitter. As shown in the drip test results in Section 4.2.2, the average emitter flow-rate was 0.1 l/h higher than the designed value of 2 l/h. The system was therefore deemed to have been installed correctly.

3.4 Trial Management and Monitoring

The two major management requirements were the irrigation scheduling and fertigation. The major consideration in applying these requirements was to ensure that the treatment was fair and that neither irrigation system was biased. The aim of the irrigation scheduling was that each irrigation system would receive equal amounts of water per irrigation event i.e. each irrigation system would have the same schedule. The advantages of both drip irrigation and ASFI is that fertigation is possible, allowing for fertiliser to be applied using the same method for both irrigation systems.

3.4.1 Irrigation scheduling

The aim of the irrigation scheduling was to maintain a soil moisture deficit of between 20 mm and 30 mm. This ensures that there is sufficient air in the soil, as well as being within the acceptable limits to avoid plant stress. This soil moisture deficit also allows for rain water to be stored, reducing runoff. Both the ASFI and drip irrigation treatments had a designed application depth of approximately 9.5 mm. This was not always the applied depth, which was often varied to visually assess the effects of altering the application time.

Of the number of simulation models available for irrigation scheduling, SA*sched* (Lecler, 2004b) was selected due to the ease of use and suitability to South African climate conditions. Lecler (2004b) reports that "SA*sched* is based on algorithms given in the Food and Agricultural Organisation paper No. 56 (Allen *et al*., 1998) with refinements to account for:

- runoff generation, deep drainage and, therefore, rainfall effectiveness,
- the effects of temperature on the rate of canopy and root development, and
- effects of both under and over-irrigation (and excessive rain) on crop yield and transpiration rates in relation to various soil and weather conditions."

The predictions from SA*sched* were checked by assessing trends in the soil moisture monitoring results (Chapter 3.4.2 and Chapter 4.4), and by checking the canopy cover algorithm. Light interception readings were taken on two dates, the 23 May 2007 and the 2 October 2007, and the results are shown in Table 3.9, using a SunScan probe (v1.01) as a check for the canopy cover predicted by SA*sched*. The canopy cover as defined by SA*sched* is the fractional light interception. Ten samples were taken in each plot using the SunScan probe. The values of canopy cover obtained for each sample were then averaged for each plot. Due to the crop being in the early developmental stage, the results for the 23 May 2007 were highly dependant on the specific points where the tests were taken. The results from the 2nd of October produced more consistent results due to the larger crop. The average for the ASFI plots was slightly lower due to the readings in Plot B being purposefully recorded in a section of the plot with less crop growth, to illustrate the variation in canopy cover throughout the field as a result of the variable soil nutrients throughout the field. This is not an indication that the drip irrigation plots had superior canopy development to the ASFI plots. The canopy cover is recorded as a fraction with a canopy cover of 1 representing a canopy cover with total coverage.

Table 3.9 Measured canopy cover results per plot

Date		**ASFI plots**					**Drip plots**					**Field Ave.**
		B	**D**	**G**	**I**	**Ave.**	**C**	**E**	**F**	**H**	**Ave.**	
23-May 2007	Canopy Cover:	0.221	0.297	0.189	0.123	0.208	0.241	0.297	0.319	0.194	0.263	0.235
02-Oct 2007	Canopy Cover:	0.532	0.744	0.734	0.682	0.673	0.717	0.75	0.721	0.678	0.717	0.695

The average field results for canopy cover in Table 3.9 were then compared to the simulated results from SA*sched*. The actual results for canopy cover were higher than the simulated values, as shown in Figure 3.20. This was surprising as no fertilizer had been applied to the field and gap filling had reduced canopy cover. However, SA*sched* does not take crop variety into account. This could be as a result of N31 being a quick growing variety, resulting in the measured fractional interception or canopy cover being higher than what was simulated with SA*sched*.

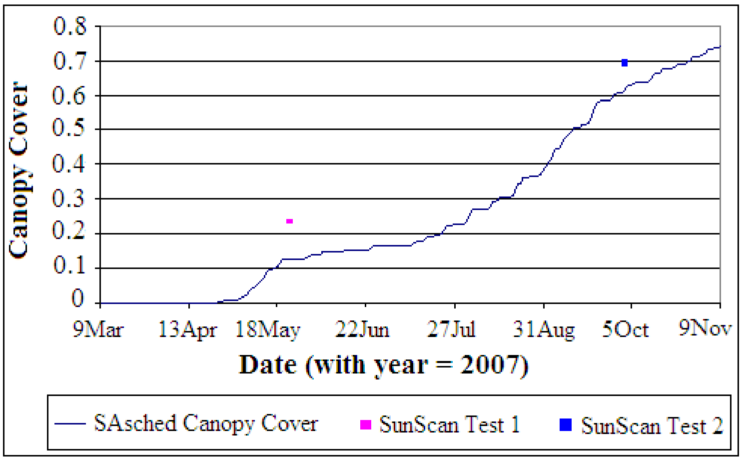

Figure 3.20 Recorded canopy cover as a check for the SA*sched* predicted canopy cover

3.4.2 Soil moisture monitoring

The third project goal was to assess the performance of ASFI compared to a reference drip system. One of the means of evaluation was to assess the trends in soil moisture over the crop cycle. Therefore, as part of the trial monitoring, soil water monitors were required at specific areas in the trial to obtain soil moisture readings to be used in the soil moisture evaluation. The soil water monitors used in this trial were watermark sensors (Thomson and Ross, 1994). To compare the soil water in absolute terms was difficult because of spatial variation of the soil and crop rooting structure and because there were only a few sensors available for the trial as a result of budget constraints. Moving the watermark sensors a few centimetres up or down the furrow or drip line could significantly alter the results. The goal, therefore, was to rather assess trends where increasing wetness indicates over-watering or decreasing wetness indicates under-watering and to compare these trends to trends obtained from SA*sched*. A direct comparison of soil moisture of the two irrigation systems would therefore not be accurate. A number of factors were considered in the placing of the watermark sensors. It was decided that the watermark sensors would be placed in three different sets along a set furrow: one near the start, another near the middle and another near the end of the furrow. The three sets along the furrow would allow for analysis of the wetting pattern at various points along the furrow. One set of watermark sensors were installed in the drip plot for comparative reasons.

The next important issue was selecting a representative furrow and drip line which were near each other to help minimise the effects of soil variability. The first factor that was assessed was the furrow slope. Due to the furrow slopes being steeper than the optimal value, the furrows with the least slope were selected as potential monitoring furrows. A field check was then conducted on these furrows to ensure that the crop growth for the furrow and accompanying drip line were representative of the area, to eliminate biasing the results of either irrigation system. These checks ensured there was consistency in crop growth between the selected drip line and furrow. The fifth furrow from the top in Blot B on the first ASFI lateral and the fifth drip line on the first drip irrigation lateral, were selected as the monitoring furrows and drip lines respectively.

Due to the different response times of the three channels of the hobo logger, each channel was individually calibrated in the laboratory using watermark sensors. The watermark sensors were also calibrated in the laboratory. The calibration resulted in the exponential relationship, represented in Figure 3.21, with the resultant exponential equation used to calculate the soil water tension (mm). In the very dry soil range, a small change in voltage (e.g. between 1.5 volts and 2 volts) results in a large change in the tension. For example, 1.5 volts represents 17

182 mm (or 171.82 kPa), 1.7 volts represents 40 860 mm and 1.9 volts represents 347 176 mm. Thus, watermark sensors are only valid for a tension between 1000 mm and 20 000 mm (Thomson and Ross, 1994).

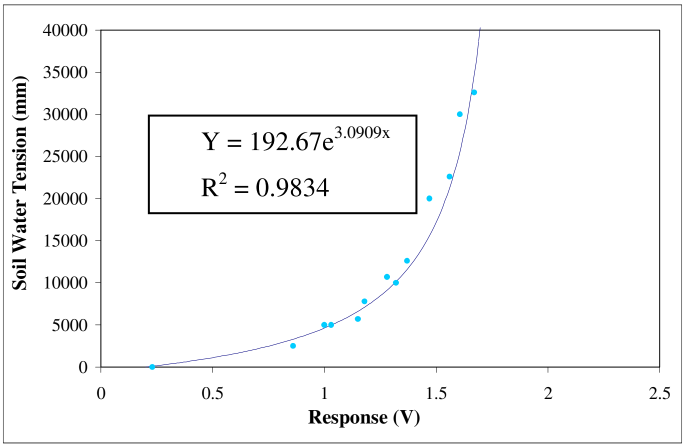

Figure 3.21 Watermark calibration

The next step was to identify regions where a variation is soil moisture was likely, using a model called Hydrus 2D (Šimůnek *et al*., 1999). Hydrus 2D is a numerical model used to predict the water transfer processes connecting the soil surface and the groundwater table. Hydrus 2D also has a sink term to account for water uptake by the plant roots (Šimůnek *et al*., 1999). Initially, assumptions such as root infrastructure were made and parameters were input into the Hydrus 2D model. This gave rough guidelines as to where water activity and changes in water content could be recorded by the watermark sensors. The results from Hydrus 2D were used to determine where there would be a response to the irrigation event between the furrow/dripper line and the root system. However, moving past the root system and further away from the furrow/dripper line, the irrigation event had little to no impact on the soil moisture. It was therefore decided to adopt the watermark arrangements in Figure 3.22. The arrangement would give an indication of the vertical and the horizontal flux. It would hopefully also give an indication of the deep percolation and compare this for the SSD and ASFI system. However, both the water flux and deep percolation are highly dependent on the localised soil conditions and variations in the plant root structure. The soil depth is approximately 55 cm, therefore the lower watermark would give a good indication as to the deep percolation.

The watermark sensors were installed as illustrated in the furrow cross-section in Figure 3.22 in three positions along the length of the furrow, one near the start, one near the middle and one near the end of the furrow. A 6 cm diameter hole was augured directly beneath the furrow to a depth of 48 cm below the natural surface level. This was done by placing a rod across the top of the furrow and auguring until the 48 cm marker on the furrow was parallel with the rod. The watermark sensor was then placed in the hole using a PVC pipe with the same diameter as the top of the watermark sensor. The cables for the sensor were run through the pipe. A portion of the soil that was augured was then wet slightly and made into a paste. This paste was placed around the watermark sensor and compacted to ensure that there was contact around the entire sensor. Small amounts of soil were then placed on top of the sensor and then compacted until the depth of the hole was 33 cm below the natural surface level. The second watermark was then placed in the hole, with the hole being covered with the above-mentioned procedure. A hole was then augured 20 cm to the side at a depth of 33 cm and also covered in the above procedure. The cables from the watermark sensors were then connected to a Hobo logger, which is placed in a watertight electronic box. The Hobo logger was used to log the results from the watermark sensors. The Hobo logger has four ports, three of which are used in this experiment for the watermark sensors. The logging interval was set at two hours which was selected as a shorter logging interval may result in polarisation of the loggers as described in Allen (1999). The configuration of the Water mark sensors in the drip treatment is shown in Figure 3.22b. The installation procedure was the same as for the furrow system. The first hole was augured next to the drip line, 5 cm away from the dripper. The watermark was placed in this position and not directly beneath the emitter so as to give representative soil moisture parallel to the drip line. Ideally, the wetting pattern of the emitters would overlap, resulting in a relatively consistent wetting profile down the drip line.

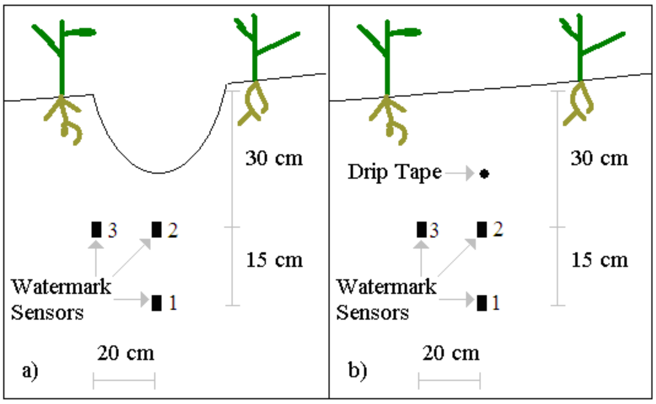

Figure 3.22 Watermark sensor installations for a) ASFI and b) SSD irrigation

3.4.3 Fertigation

An essential part of the trial was to insure that neither treatment was biased. An important part of this was ensuring that each system received an equal amount of nutrients and that crop growth was not limited by nutrient deficiencies. This was particularly important due to the Ukulinga trial site being virgin land with natural variation in soil nutrients. Fortunately, both irrigation treatments are suitable for fertigation, although this can sometimes clog the drip emitters. Fertigation is a fertilizer application method whereby the fertiliser is applied using the irrigation water. The venturi, which uses the pressure difference across a point such as a pressure regulating valve, was used to create suction, whereby fertiliser in solution or liquid fertiliser could be sucked into the irrigation water. The venturi is illustrated in Figure 3.21.

A preliminary Nitrogen fertigation schedule was determined and is shown in Table 3.10. However, due to time delays in finding an appropriate flow controller as well as the high rainfall for the year delaying fertigation opportunities, this initial schedule was not followed. This may impact the accuracy of the harvest results as crop growth was dependant on the natural soil nutrients which may have been highly variable as the field was virgin land. The fertigation schedule contained in Table 3.10 is for each irrigation systems' fertigation requirements and this quantity would need to be doubled when accounting for both the drip and ASFI systems.

Table 3.10 Initial Urea (46 % Nitrogen) Fertigation schedule.

Month	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Total**
Target N (kg/ha)	140 kg/ha							
% of total	35	10	10	10	15	15	5	100
kg N/ha	49.00	14.00	14.00	14.00	21.00	21.00	7.00	140
kg Urea/ha	106.52	30.43	30.43	30.43	45.65	45.65	15.22	304
Min # Irrig	**2**	**4**	**4**	**4**	**8**	**8**	**8**	38
kg Urea/irrig/ha	53.26	7.61	7.61	7.61	5.71	5.71	1.90	
Ha to fertilize =	**0.2592**							
Tot kg Urea/irrig	13.81	1.97	1.97	1.97	1.48	1.48	0.49	
Tot bags Urea/irr	0.28	0.04	0.04	0.04	0.03	0.03	0.01	
Bags Urea/mth	**0.6**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.1**	**1.58**

Leaf samples were conducted on 30th November 2007 to assess the crop nutrient requirements and to assess if the lack of fertiliser application resulted in nutrient deficiencies. This took place prior to the application of any fertiliser. The procedure of Anon (2003) was used for the leaf sampling. The leaf samples were taken to assess the nutrient requirements of the crop and to consider the implications of fertigation having not taken place. Leaves were taken from stalks of average height. The sampled leaves were the third leaf down, with the first being at least half unrolled. Forty leaves were collected at random spots in the trial plots. Good and bad leaf samples were taken for Plot B due to the uneven growth in that plot. The tops and bottoms of the leaves were then cut off, leaving a central portion 300 mm long. The midribs of the leaves were then stripped out from the central portion and discarded. The leaf sample was then spread out on a clean sheet, allowed to dry and then bundled. The leaf samples were then taken to the laboratory for analysis.

The leaf analysis test results confirmed that there was a shortage of Nitrogen, where all the leaf analysis results for Nitrogen were below the leaf Nitrogen thresholds of 1.9 %. The satisfactory range is obtained from Anon, (2003). The results for the main nutrients, Nitrogen (N), Phosphorus (P) and Potassium (K) are listed in Table 3.11. The results for P and K were within an acceptable range. However, it is possible that if the N levels were sufficient, there would be better crop growth, which could result in reduced P and K levels. The leaf analysis results indicated that the N levels were a major cause of the variable growth in Plot B as well as the whole field.

Table 3.11 Leaf sampling results

Site	**N (%)**	**P (%)**	**K (%)**
Plot B good	1.73	0.25	1.57
Plot B std	1.47	0.26	1.49
Plot B bad	1.35	0.23	1.24
Plot C	1.32	0.25	1.59
Plot D	1.46	0.25	1.45
Plot E	1.38	0.24	1.45
Plot F	1.54	0.29	1.31
Plot G	1.53	0.28	1.51
Plot H	1.63	0.29	1.37
Plot I	1.52	0.29	1.3
Satisfactory Range	>1.9	0.19-0.24	1.05-1.59

ASFI requires a consistent supply of fertiliser during the irrigation event to ensure that the fertiliser is distributed evenly along the furrow. It was therefore necessary to control the flow-rate of fertiliser entering the irrigation system and to ensure that the fertiliser had a consistent solution in the supply tank. After extensive research, it was decided to test an Acu-flow flow controller (Jain Irrigation Inc., 2003), as shown in Figure 3.23. The Acu-flow flow controller was connected to an 8 mm tube on each end. The one end of the tube was then connected to the venturi and the other end to a small filter. The filter end of the tube was then placed in a container filled with urea in solution.

Figure 3.23 Acu-flow flow controller

This flow controller was tested for a range of pressure differences across the flow control valve to assess the suitability of the device as a fertigation flow controller. The flow control valve was used to create the range in pressure differences. The results from the test are contained in Table 3.12. The Acu-flow was able to regulate the flow adequately, except for when the pressure difference across the venturi was below 200 kPa. In most circumstances, it would not be practically beneficial to have this pressure difference, as it would result in more pumping costs due to the increased required pumping head. In these cases, it may be more beneficial to use fertilizer injectors as there would not be this additional head requirement. The elevation of the fertilizer container did not impact the results. Therefore, the container could be open to the atmosphere and the decreasing water level in the container would not have a significant impact.

Table 3.12 Pressure tests on Acu-flow flow controller

Pressure (kPa)			**Time**	**Volume**	**Flow-rate**	**Elevation**
Before valve	**After valve**	**Difference**	**(seconds)**	**(ml)**	**(ml/s)**	**(m)**
400	260	140	48.8	300	6.15	0
440	230	210	31.9	400	12.54	0
450	220	230	31.8	400	12.58	0
470	210	260	32	400	12.50	0
470	210	260	31.6	400	12.66	1.2

Once the Acu-flow was installed, fertigation commenced. The actual fertigation schedule is as in Table 3.13. Fertigation only commenced in January 2008 and was concluded in February 2008. No fertiliser was applied in March 2008 as this would not have a significant impact on the sucrose content of the harvested sugarcane. A total of approximately 1.2 bags of urea were applied equally to each of the irrigation treatments.

Table 3.13 Actual fertigation schedule

Month	**December**	**January**	**February**	**March**	**Total**
Target N (kg/ha)	140.00	kg/ha			
% of total	0	42	32	0	74
kg N/ha	0.00	59.08	44.38	0.00	103
kg Urea/ha	0.00	128.43	96.48	0.00	225
Min # Irrig	**1**	**3**	**2**	**1**	7
kg Urea/irrig/ha	0.00	42.81	48.24	0.00	
Ha to fertilize =	**0.2592**				
Tot kg Urea/irrig	0.00	11.10	12.50	0.00	
Tot bags Urea/irr	0.00	0.22	0.25	0.00	
Bags Urea/mth	**0.0**	**0.7**	**0.5**	**0.0**	**1.17**

3.5 Harvesting Procedure

The next phase in the methodology is the harvesting procedure. Five rows from each plot were selected and weighed individually. In the top half of the field, the five rows excluding the guard (or end) rows were selected. In the bottom half of the field, Rows 2, 4, 6, 8 and 10 were selected. These were selected due to the ease of harvesting with a row between each harvested row. The cane was harvested by hand as shown in Figure 3.24, without removing tops and trash, and placed into bundles.

Figure 3.24 Hand harvesting of sugarcane

Twelve random stalk samples, approximately two stalks from each bundle, were selected from each of the five rows for each plot and weighed, as illustrated in Figure 3.25. The tops and trash were then removed and the stalks were re-weighed. The samples were then sent to the South African Sugar Research Institute (SASRI) laboratory for analysis of the sucrose content.

Figure 3.25 Weighing of cane for sucrose sampling and sucrose sample cane trashing and topping

A 4X4 vehicle, with a weighing grab, shown in Figure 3.26, was used to weigh the cane bundles. The length of each row was also recorded. Care was taken during the weighing process to ensure that the weighing grab was still when the recordings were taken. This was also the first occasion the weighing device was used since it had been calibrated and therefore the results should be reliable.

Figure 3.26 Weighing device for sugarcane bundles

The weight of the sugarcane bundles were combined as a total weight for each row that was selected for harvesting.

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The purpose of including Chapter 3 was to achieve the second goal of the project: to design and commission a prototype ASFI system for sugarcane in a field trail at Ukulinga, the University of KwaZulu Natal research farm, including furrows, pipe network and the novel, automatic control valve to facilitate the operation of the system. A boot and piston valve was developed and was used to direct flow in a low-density polyethylene (LDPE) pipe network. A random plot layout was designed and implemented for the ASFI and reference drip irrigation treatments. Trial management practices included fertigation and irrigation scheduling, where SA*sched* was used as an irrigation management tool. The soil moisture was monitored using watermark sensors, the results of which are included in Chapter 4, in addition to the valve test results and irrigation test results.

4. FIELD TEST RESULTS

The third project goal was to assess the performance of the ASFI system relative to a reference SSD irrigation system for the Ukulinga trial. This chapter contains the results from the evaluation of the ASFI system and the comparison with the reference SSD system, including pressure and performance tests on the ASFI prototype valve, ASFI and SSD irrigation performance tests, soil moisture analysis and the results for crop and sucrose yield. The resultant impact of harvesting on crop re-establishment was also assessed.

4.1 Valve Testing

There were two major objectives to the valve testing procedure. The first part of the test was to determine the pressure loss across the valve. Ideally, this should be as small as possible to enable the pressure loss down a sub-main to be relatively small. Initially the theoretical head loss through the valve was calculated. The valve was then tested at various pressures and the pressure loss through the valve measured. Tests were conducted with the flow directed down the lateral and with the flow continuing down the sub-main. The results are for the final valve design used in the field, as it has the lowest head loss across the valve. The second part of the test was to analyse the pressure range within which the valve could operate.

The theoretical head loss, was calculated using velocity loss factors (*k*) obtained from ARC (2003), and a flow-rate of 16.2 m^3/h from the design in Section 3.3.1. The valve consists of 1 T-piece entering the valve, 1 reduction from 65 mm to 40 mm in the valve, 1 expansion back to 65 mm and 1 bend out of the valve. The pipe cross-section areas were then used to calculate the velocity for $kv^2/2g$. The Head loss through the valve was calculated in Table 4.1.

Table 4.1 Theoretical pressure drop across the valve

Velocity loss factor *k*				**$V^2/2g$ (65 mm)**	**$v^2/2g$ (40 mm)**
Bend (k_b)	T- piece (k_T)	Reduction (k_r)	Expansion (k_e)		
0.9	1.2	0.18	0.25	0.094	0.654
$h_{valve} = (k_T \times V^2/2g) + (k_r \times v^2/2g) + (k_e \times v^2/2g) + (k_b \times V^2/2g)$				= 0.48 m	

The actual pressure drop across the valve was then measured with various pressures set at the hydrant. For the test, the flow-rate was varied and each row of Table 4.2 represents a single test. The pressure loss through the valve proved to be 2 to 3 times higher than estimated from theory. With a pressure of approximately 5 m before the valve, a pressure loss of 1.6 m was experienced down the lateral and a pressure loss of 1 m was experienced with the flow continuing down the sub-main. This is possibly due to the close proximity of the bends and reducers, which may result in additional turbulent flow. In terms of conventional irrigation systems, this pressure loss would not be acceptable. However, the ASFI system could be designed to negate these losses and these losses would be significantly reduced if a larger diameter valve were used. However, this was not possible during the course of this experiment as the larger valve would require a larger boot which would need to be injection-moulded.

Table 4.2 Pressure drop across the valve with a) flow outlet directed down the lateral and b) flow outlet directed down the sub-main.

a) Pressure (m)		
Before Valve	**After Valve: Lateral**	**Pressure Drop**
3.0	1.9	1.1
3.5	2.3	1.2
4.2	2.8	1.4
4.8	3.2	1.6

b) Pressure (m)		
Before Valve	**After valve: Sub-main**	**Pressure Drop**
3.3	2.7	0.6
3.7	3.0	0.7
4.4	3.6	0.8
5.0	4.0	1.0

The valve was then tested to assess the pressure range in which it could open at the correct cut-off time. The valve was tested with an inlet pressure of between 3 m and 8.7 m. In this pressure range, the valve could open and close in the required cut-off time of 42 minutes. This pressure range would be within the anticipated pressure range for ASFI. If the pressure is significantly less than 3 m, it would probably be preferable to use a larger boot/piston ratio to allow for the upward pressure on the valve to overcome the downward pressure on the piston, allowing the valve to open. If the pressure is significantly more than 10 m, it is expected that the valve would be able to operate normally. However, this may cause extra wear on a number of components. The higher the pressure, the quicker the valve-shutting process occurs.

4.2 Irrigation Performance Tests

The irrigation performance tests included infield measurements and analyses of these results for both the ASFI and the reference SSD system. These results were then used to assess how the ASFI system performance compared to the performance of the reference SSD system.

4.2.1 ASFI tests

The ASFI tests included metric measurements of the advance and recession fronts for predetermined furrows and specified irrigation events. These results were used to obtain the associated estimates of *DU* using SIRMOD III. Due to the infield gap filling requirements (discussed in Chapter 3.3.5), only two laterals were used to distribute water to the four plots (instead of three laterals distributing water to five plots). From each of the two laterals, three furrows were selected for infield testing and analysis, with the intention of providing a wide range in advance/recession times. These were Furrows B5, I4 and I10 for the first lateral, while Furrows D4, G4 and G6 were selected from the second lateral. Temporal variation was also assessed for the Ukulinga ASFI trial, with measurements recorded for the advance front for Furrow B5 at specific irrigation events at different times during the season.

The advance/recession front tests were conducted as follows. The inflow-rates of the selected furrows were firstly measured using a bucket placed in a hole next to the furrow so that the head was the same as during regular operation. The emitter was then used to fill the bucket for set time intervals. The amount of water in the bucket was then measured using a measuring cylinder. Advance/recession front measurements were then conducted with recordings conducted at 5 m intervals. The recession front was not recorded where there was ponding at the end of the furrow, as these recordings would be susceptible to the observer subjectivity. The advance/recession front test results for furrow B5 are included in Table 4.3 as an example of the output from the test. The width and depth of the irrigation water in the furrows was also recorded at various points along the furrow. Furrow B5 was the furrow in which the soil moisture sensors were installed as described in Chapter 3.4.2. The results from the flow-rate test and advance/recession front tests, conducted on 15 August 2007, are contained in Table 4.3. Furrow B5 has a slope of 1:42.25

Table 4.3 Advance/recession front field test results for Furrow B5 (length = 29.7 m)

Furrow B5: Advance and Recession		
Distance (m)	Advance (min:sec)	Recession (min:sec)
5	02:17	42:23
10	05:38	45:05
15	09:04	46:53
20	13:30	47:30
25	25:38	48:18
End	35:07	
Cut–off	40:00	
Stopped	40:15	

Furrow B5: Flow-rate		
Time (sec)	Volume (l)	Discharge (l/min)
30 sec	5.64	11.28
60 sec	11.09	11.09
	Ave	11.185
Flow width range (cm):		10 - 15
Flow depth range (cm)		1.5 – 3.5

The results for the advance/recession front tests for furrow B5 were then graphed as illustrated in Figure 4.1. The water distribution for the test was not optimal as there was not an equal water/soil contact time at the various positions along the furrow.

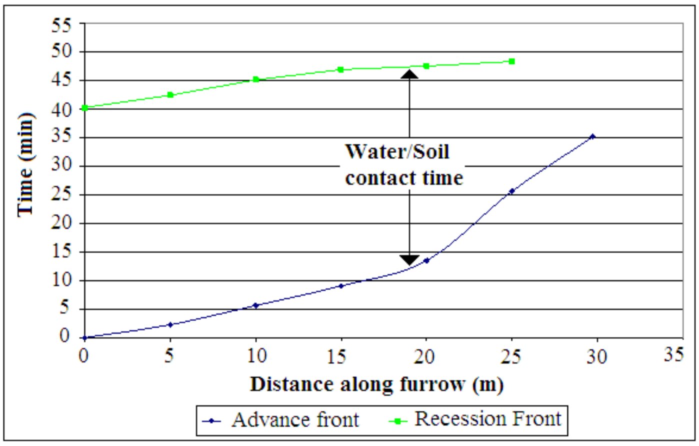

Figure 4.1 Advance/recession front test for furrow B5

Furrow I4, with a slightly quicker advance front, was the second furrow selected for advance/recession front tests on ASFI line 1. The results for the I4 advance/recession front test are in Table 4.4. Furrow I4 has a slightly higher flow-rate and the slightly steeper slope of approximately 1:38. Furrow I10 has a slope of 1:40.5. The flow-rate into Furrow I10 is slightly higher than Furrow B5, yet Furrow I10 still has a similar advance/recession front, probably due to the differences in slope.

During the test on the 15th August 2007 it was noted that the flow from the emitter into Furrow D4 was significantly less than for previous irrigations. The cause was found to be a defect in the connector between the emitter to the lateral. This resulted in a reduced flow-rate of 8.815 l/min which also impacted the flow-rates from the surrounding emitters. However, the test was continued, as it was expected that this would show the robustness of the system. However, a full set of advance/recession front results were required in order to complete the SIRMOD III simulations and the cut-off time was therefore increased to 52 minutes for the second lateral. This defect could be eliminated by testing the emitters before installation. After the test, the emitter was removed and replaced. The increased cut-off time of 52 minutes had a significant impact on Furrow G4. This furrow was selected as it had a quick advance front as a result of the large, 12.1 l/min, inflow-rate. Thus, increasing the cut-off time would result in ponding at the end of the furrow which would negatively impact the furrow performance. The furrow slope was 1:39.5. Furrow G6 was selected as it had a slow advance front. Furrow G6 was therefore not adversely affected by the increased cut-off time. The furrow had an inflow-rate of 10.1 l/min which was slightly less than average. However, this probably accounted for the slow advance time.

Table 4.4 Advance/recession front tests for the Ukulinga test furrows (15 August 2007).

Furrow	I4		I10		D4		G4		G6	
Inflow-rate:	11.95 l/min		12.32 l/min		8.815 l/min		12.09 l/min		10.1 l/min	
Furrow Length:	29.2 m		29.7 m		30 m		29.9 m		29.8 m	
Dist (m)	**Adv.**	**Rec.**	**Adv.**	**Rec.**	**Adv.**	**Rec.**	**Adv.**	**Rec.**	**Adv.**	**Rec.**
5	03:06	48:00	02:58	43:02	03:02	56:05	02:10	57:46	03:03	56:42
10	06:30	49:00	06:06	44:48	07:18	57:01	05:25	59:23	06:31	57:45
15	10:24	50:00	09:29	46:57	13:41	58:15	08:48	60:00	10:33	58:23
20	15:58	52:00	15:39	49:16	23:51	58:22	12:31	60:04	20:20	59:52
25	24:00		23:32		33:23	59:05	16:50		29:37	60:09
End	30:10		31:48		58:50	60:00	23:39		46:35	
Cut–off	40:00		40:00		52:00		52:00		52:00	
Stopped	40:30		41:15		55:01		55:27		55:27	

The results from the advance/recession front tests were then used with SIRMOD III to determine the theoretical *DU*. Parameters such as furrow slope, furrow shape and furrow inflow-rate were entered into SIRMOD III. The two-point compute infiltration function was then run. The output advance/recession front from SIRMOD III was compared to the recorded field trial advance/recession front. Parameters "*a*" and "*K*", from the Kostiakov equation (Walker, 2003) were then adjusted slightly, and the two-point compute function run again until the simulated advance/recession front had the best fit with the recorded field trial advance/recession front.

Table 4.5 contains the results of the advance/recession front tests for ASFI line 1. This includes the results of the Furrow B5 advance/recession front tests at various stages during the crop cycle. Although the furrow slope was considerably steeper than the optimum designed slope of approximately 1:250, the ASFI Line 1 performance test produced a *DU* range of between 71.55 % and 80.25 %. The test with the lowest *DU* for Furrow B5 was on the 12 September 2007, when the soil was at its driest, according to SA*sched*, with a water deficit of approximately 24 mm. The cut-off time would need to be increased to approximately 45 minutes to improve the irrigation performance of Furrow B5 with a water deficit of 24 mm.

Table 4.5 SIRMOD III results for Furrow 1 using tests conducted on a) 17 July 2007, b) 8 August 2007, c) 15 August 2007 and d) 12 September 2007

	Furrow B5				I4	I10
Date	17-Jul-07	08-Aug-07	15-Aug-07	12-Sep-07	15-Aug-07	15-Aug-07
***DU* (%)**	80.25	74.84	76.42	71.55	77.48	80.4

A SIRMOD III simulation of ASFI line 2 revealed that although the flow-rate for Furrow D4 is significantly below the optimum value, the factor that the *DU* is most sensitive to (Section 3.2.2), the test still produces a *DU* of 65 %. This, in part, is due to the increased cut-off time of 55 minutes. The *DU* results in Table 4.6 would be considered average results for conventional surface irrigation, even though the variables such as cut-off time, inflow-rate and slope were significantly different from consistent and optimum, indicating the robustness of ASFI.

Table 4.6 SIRMOD III results for the ASFI Lateral 2 for 15 August 2007 test

Furrow	D4	G4	G6
***DU* (%)**	64.65	58.37	75.45

4.2.2 Drip irrigation tests

A comprehensive evaluation of the SSD irrigation trial was conducted as suggested in Koegelenberg and Breedt (2007). The field test was conducted on 21 May 2008, approximately two weeks after re-establishment was complete, to assess the performance of the SSD system after a year of usage. The general information of the drip system is contained in Table 4.7.

Table 4.7 General Information on the drip system

General Information	
Type of micro system	Sub-surface drip
Type, flow path and make of emitter	Netafim Tiran 12010
Pressure regulated emitters	No
Length of laterals (m)	30 m
Spacing of Laterals (m)	1.8 m
Emitter spacing in/on lateral (m)	0.5 m
Wetted radius (m)	0.27 m (manufacturer specification)

Pressure readings for Drip Lines 1 and 2 are recorded in Tables 4.8 and 4.9 respectively. There were minimal differences between the designed and measured pressure at the hydrant. Pressure readings were not taken at points along the lateral as there were no connectors to connect the needle gauge to 12 mm laterals, only for 17 mm laterals. Laterals were short and down the slope and therefore pressure variation in the lateral would likely be negligible. There was a 6.8 % variation in the pressure at the end of the laterals from the average value of 112.7 kPa for the first line which was within the acceptable limits of 20 % as stipulated in Koegelenberg and Breedt (2007).

Table 4.8 Pressure readings for Drip Line 1

Pressure Readings					
Pressure at Hydrant (kPa)	Measured			Design Specifications	
	165			159	
Pressure control at hydrant	Yes				
Pressure at the end of the laterals (kPa)	Lateral 1	Lateral 2	Lateral 3	Lateral 4	Lateral 5
	120	118.5	110	110	105

As shown in Table 4.9 there were larger pressure losses within laterals on Drip Line 2. This was mainly due to leaks caused by rodents biting the laterals for water. Although the first line was also affected, there were significantly more holes in the second line, in particular, the bottom half of the field. Although none of the drip laterals that were tested had holes, a number of surrounding laterals had holes, resulting in reduced pressure in the system. For the second line, there was a 17 % variation in the end of lateral pressure which is within the acceptable limits of 20 % as stipulated in Koegelenberg and Breedt (2007).

Table 4.9 Pressure readings for Line 2

Pressure Readings						
Pressure at Hydrant (kPa)	Measured			Design Specifications		
	165			159		
Pressure control at hydrant	Yes					
Pressure on laterals (kPa)	Position	Lat. 1	Lat. 2	Lat. 3	Lat. 4	Lat. 5
	L	117	115	102	84	82

Discharge tests were then recorded using 5 drippers on 5 laterals, 25 points in total, with measurements contained in Table 4.10 and Table 4.11

Table 4.10 Discharge test for Drip Line 1

Distance	**Discharge (l/hr)**				
	Lat. 1	Lat. 2	Lat. 3	Lat. 4	Lat. 5
0	2.25	2.4	2.19	2.1	2.01
L/4	2.16	2.31	2.22	2.1	1.98
L/2	1.8	2.4	2.25	2.16	2.1
3L/4	2.37	2.34	2.31	2.16	2.13
L	2.4	2.4	2.1	2.1	1.95

Table 4.11 Discharge test for Drip line 2

Distance	**Discharge (l/hr)**				
	Lat. 1	Lat. 2	Lat. 3	Lat. 4	Lat. 5
0	2.1	1.95	2.19	1.98	2.01
L/4	2.34	2.13	2.31	1.89	1.92
L/2	2.28	2.19	2.4	1.95	1.95
3L/4	2.16	2.31	2.4	1.95	1.98
L	2.28	2.22	2.22	2.1	1.95

The flushing velocity of above 0.4 m/s is required to remove sediment from the laterals when the end of the lateral is opened, reducing emitter clogging. The flushing velocity, in Table 4.12 and Table 4.13, was calculated using Equation 4.1.

$$v = \frac{353,68Q}{d^2} \tag{4.1}$$

where: v = flushing velocity (m/s),

Q = flow-rate (m^3/h), and

d = inner diameter of lateral (mm).

The flushing velocity for each of the laterals was significantly higher than the minimum value of 0.4 m/s according to Koegelenberg and Breedt (2007), and was therefore acceptable.

Table 4.12 Flushing velocity for Drip line 1

Variable	**Units**	Lat. 1	Lat. 2	Lat. 3	Lat. 4	Lat. 5
Flow-rate out end of lateral	l/s	0.120	0.125	0.119	0.114	0.105
Flow-rate out end of lateral	m^3/h	0.433	0.450	0.429	0.412	0.379
Inner diameter of lateral	mm	11.1	11.1	11.1	11.1	11.1
Flushing velocity	m/s	1.243	1.291	1.231	1.181	1.088

Table 4.13 Flushing velocity for Drip line 2

Variable	**Units**	Lat. 1	Lat. 2	Lat. 3	Lat. 4	Lat. 5
Flow-rate out end of lateral	l/s	0.133	0.125	0.120	0.108	0.103
Flow-rate out end of lateral	m^3/h	0.478	0.451	0.431	0.389	0.369
Inner diameter of lateral	mm	11.1	11.1	11.1	11.1	11.1
Flushing velocity	m/s	1.372	1.294	1.236	1.116	1.060

The discharge uniformity of a drip irrigation system is measured and calculated using the Coefficient of Variation (*CV*) as in Equation 4.2 from Koegelenberg and Breedt (2007). The *CV* was calculated as:

$$CV \quad = \left(\frac{\sqrt{\frac{1}{n-1} \times \sum_{i=1}^{n} \left| x_i - \bar{x} \right|^2}}{\bar{x}} \right) \times 100 \tag{4.2}$$

$$CV \quad = \left(\frac{\sqrt{\frac{1}{25-1} \times 0.601}}{2.188} \right) \times 100$$

where: n = number of tested emitter,

x_i = flow-rate of each emitter (l/h), and

$\bar{x}$ = mean flow-rate of the 25 samples in l/h.

Therefore CV = 7.23 %, which, according to the criteria in Table 4.14, is classified as excellent.

The statistical uniformity (U_s) was then calculated as in Equation 4.3:

$$U_s = 100 \times \left(1 - \frac{CV}{100} \right) \tag{4.3}$$

$$U_s = 100 \times \left(1 - \frac{7.23}{100} \right)$$

Therefore U_s = 92.8 %, which, according to the criteria in Table 4.14, is classified as excellent.

The emission uniformity is used to determine how uniformly water is delivered to the plants and is determined using Equation 4.4:

$$EU = 100 \times \left(\frac{Average\ flow\ rate\ (lowest 25\%)}{Average\ flow\ rate\ of\ the\ normal\ block} \right) \tag{4.4}$$

$$EU = 100 \times \left(\frac{\frac{1.8 + 2.01 + 2.1 + 1.98 + 1.95}{5}}{2.188} \right)$$

Therefore *EU* =89.9 %, which, according to the criteria in Table 4.14, is classified as excellent.

The guidelines in Table 4.14 allow for the system to be assessed and classified according to the system performance.

Table 4.14 Guidelines for *CV*, U_s and *EU* values (*ASAE standards*, 1997)

Classification	***CV* (%)**	**U_s (%)**	***EU* (%)**
Excellent	< 10	> 90	> 87
Good	10 – 20	80 – 90	75 – 87
Fair	20 – 30	70 – 80	62 – 75
Poor	30 - 40	60 – 70	50 – 62
Unacceptable	> 40	< 60	< 50

The *CV*, U_s and *EU* were calculated using the same procedure for Line 2. These were calculated as 8.3 %, 91.7 % and 90.9 % respectively. These are all classified as excellent according to *ASAE standards* (1997). Calculating the q_{var} was not part of the procedure laid out in Koegelenberg and Breedt (2007) and the results can't be used to compare to the results from the ASFI treatment. However, the q_{var} for Line 1 and 2 was 25 % and 19 % respectively, substantially greater that the allowable q_{var} of 10 %.

4.2.3 Comparison of the performance of the irrigation systems

The main purpose of the irrigation performance tests was to compare the performance of ASFI to the reference SSD irrigation system for the Ukulinga trial. A common performance indicator was required. There is a correlation between *DU* and *EU*. As is shown in Equation

2.1, *DU* is a ratio of the average infiltrated depths of the lowest 25 % of recordings to the average infiltrated depth recorded. *EU* is the ratio of the average for the lowest 25 % of flow-rate recording to the average flow-rate (or volume/time) recordings. Therefore *DU* = *EU* for the drip treatment if the emitter spacing within the plot is equal and if the irrigation time is equal for each emitter. The *EU* for the SSD system is 89.9 % for the first lateral and 91.7 % for the second lateral. This is noticeably higher than the *DU* of between 72 % and 80 % for the results obtained for Lateral 1 in the ASFI trial. However, it is necessary to consider the yield results in Section 4.5 to assess whether the differences between the irrigation performances had an impact on crop production. Prior to this, however, the soil moisture monitoring results will be analysed in Section 4.4 to assess if differences between the *DU* results for the two treatments were reflected in the soil moisture trends.

4.3 Soil Moisture Monitoring and Irrigation Scheduling

There were two major applications for using soil moisture monitoring in the Ukulinga trial. The first application was to assess if there were significant soil moisture differences between the two irrigation treatments. However, the second, and more important application of the watermark sensors, was a check for the soil moisture results simulated using the *SAsched* model. For example, if *SAsched* simulated that the soil moisture was being maintained at a water deficit of 20 mm, but the measurement by the sensors show a reduction in water content, then the irrigation scheduling in *SAsched* should be adjusted accordingly. This was not required for the Ukulinga trial.

Unfortunately, the hobo data logger positioned at the start of the furrow (position A in Figure 3.22) malfunctioned due to contact with water. Therefore, the results in this section are for the sensors in the drip irrigation plot, at position B (as in Figure 3.22), located near the middle of the furrow and at position C, located near the end of the furrow.

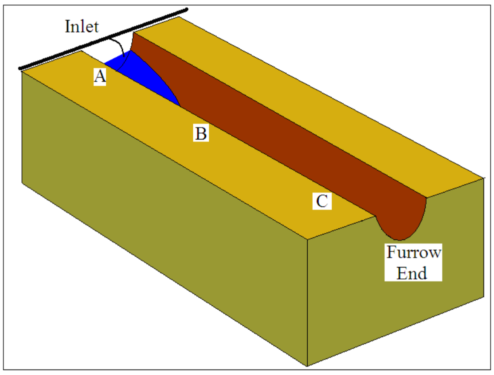

Figure 4.2	Positioning of hobo loggers along furrow

The results of the soil water tension, obtained from the exponential equation in Figure 3.21, were then plotted over time with the drip irrigation readings in Figure 4.3, Furrow B readings in Figure 4.4 and Furrow C readings in Figure 4.5. The positions of Watermark 1, 2 and 3 are diagrammatically represented in Figure 3.22. Watermark 3 generally has the highest variation in soil moisture. This is probably due to a larger root activity in the area. For the drip irrigation plot, Watermark 1 consistently has a lower tension and hence a higher moisture content than the shallower sensors, suggesting higher deep percolation (water lost below the root zone). However, the high moisture readings for Watermark 1 in the drip plot may be dependent on the localised soil conditions and would need to be verified by increasing the number of sensors for each treatment.

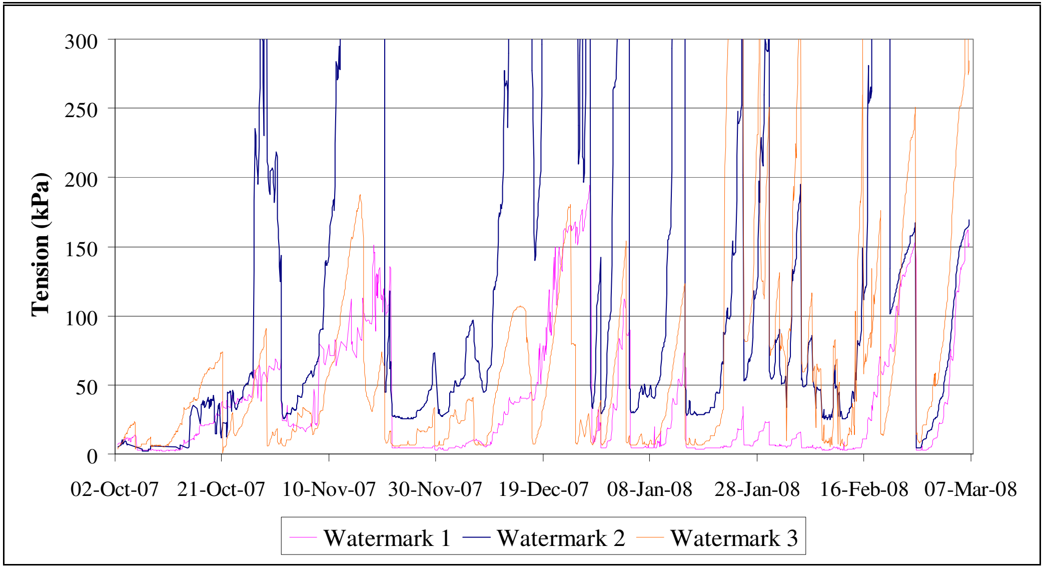

Figure 4.3	Soil water tension in the drip irrigation trial

Furrow B soil moisture results, in Figure 4.4, had relatively little variation in the tension of Watermarks 1 and 2 and a large tension variation for Watermark 3. It was unlikely that this was due to the local soil conditions as Watermark 2 was situated directly under the furrow, yet does not have a significant voltage response to an irrigation event, rainfall or a dry period. The problems with Watermarks 1 and 2 are probably a result of faulty connections that were used to connect the watermark sensors to the hobo logger. However, the results for Watermark 1 improved after the 26 December 2007, when the connection from the Watermark to the Hobo data logger was adjusted, and appeared to follow the trends when comparing it to irrigation and rainfall events and the dry periods. These problems highlight the need to download data more regularly, and to therefore identify and eradicate problems sooner.

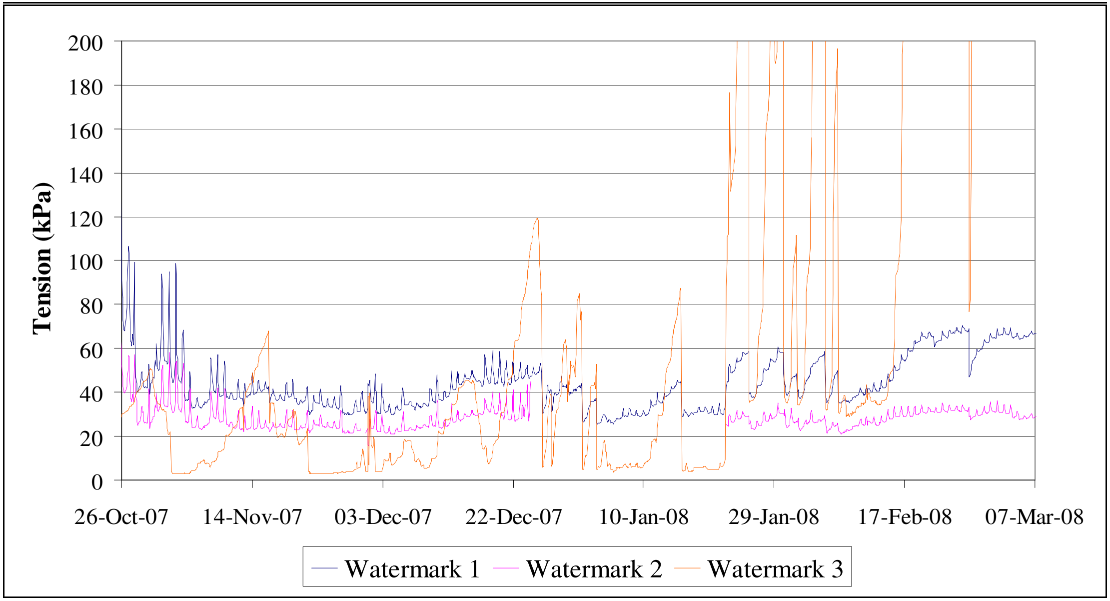

Figure 4.4 Soil water tension for Furrow B in the ASFI trial

The Watermark sensors at Furrow C were at the end of the relatively slow Furrow B5. Furrow B5 was slightly slower due to the lower furrow inflow-rate of 11.2 l/min, as opposed to the average of 11.5 l/min. Therefore, the soil conditions tended to dry towards the end of the furrow. When a large rainfall event or a series of irrigation events occurred, the soil would then wet up considerably, as shown in Figure 4.5. This was as a result of the steep furrow slope and the subsequent ponding at the end of the furrow after a large rainfall/irrigation event.

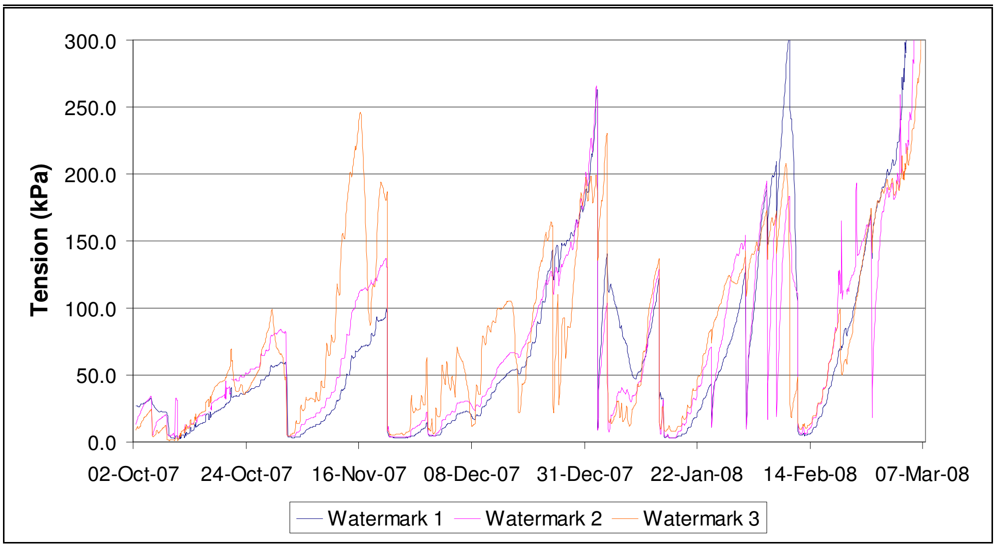

Figure 4.5 Soil water tension for Furrow B in the ASFI trial

The Watermark 3 sensors (the sensors to the side of the furrow) were then compared for the drip and two furrow test sites, as shown in Figure 4.6. The soil tended to dry up between October 2007 and March 2008. An irrigation schedule was used whereby the soil was allowed to dry during the last 2 months of the crop ratoon as a water saving procedure. This would have minimal impact on the sucrose yield, even if the crop experienced stress. It was noted that the drip and Furrow B sites dried up significantly from the 22nd of January 2008, with an increased fluctuation in the tension. This was due to the tension being extremely sensitive to a slight variation in soil moisture when the soil was dry. This is verified when analysing the data in Figure 4.7 and 4.8.

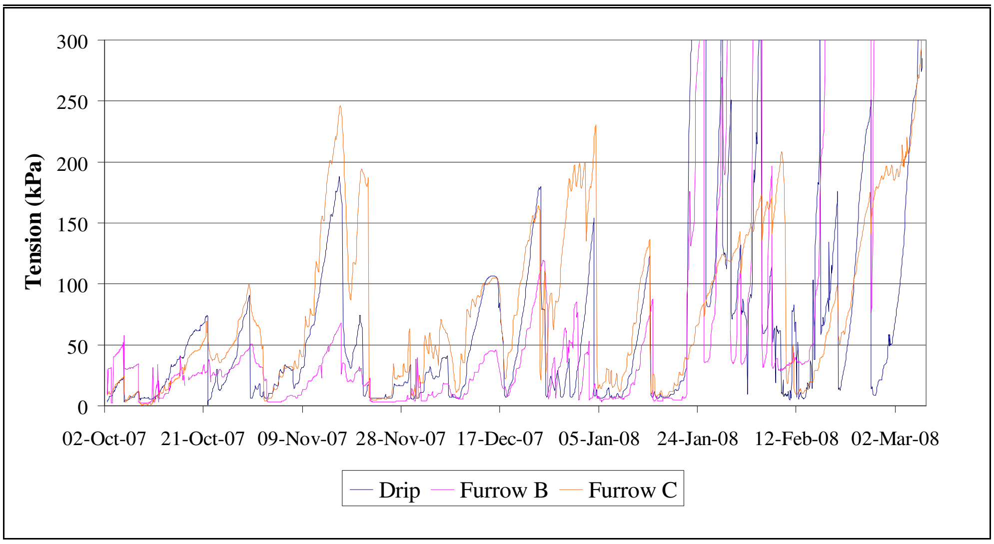

Figure 4.6 Comparison of soil water tension for Watermark 3 sites at the Drip, Furrow B and Furrow C test sites.

The Watermark 3 voltage response to irrigation events for Furrow B is shown Figure 4.7, during the dry period from the 22nd of January 2008 onwards, with reduced irrigation events. The tension results were not recorded as these had large fluctuations during this time period due to the exponential relationship between tension and voltage. Although the values associated with the voltage output are meaningless, using the voltage output provide a better illustration of the trends during this selected time period, in particular, the response to rainfall and irrigation events. In Figure 4.7, the furrow dries off slowly. However, the soil is relatively dry for the majority of time. It is noted that there is a greater response to an irrigation event as opposed to a rainfall event. The results suggest that the irrigation event contributes more effectively to the active root area than a rainfall event. This would be most beneficial during the early stages of a plant crop, when the plant root structure is relatively undeveloped.

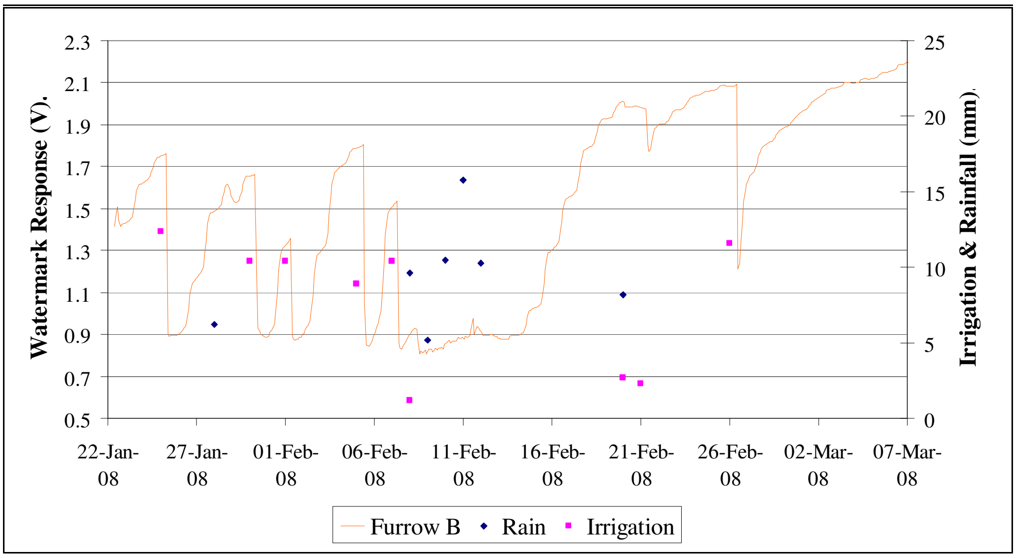

Figure 4.7 Response of the Furrow B Watermark 3 to rainfall and irrigation events near the end of the crop cycle

Water tension for Drip Watermark 1 was then plotted with irrigation and rainfall events super-imposed, with emphasis on the results obtained after 22 January 2008. The sharp drops in the tension in the drip plots collaborate with rainfall and irrigation events during this time period, as shown in Figure 4.8. However, the soil moisture seldom returns to DUL as it did prior to the 22nd of January. The soil water also appears to dry out quicker towards the end of crop cycle. This would be as a result of the warmer conditions and increased root activity.

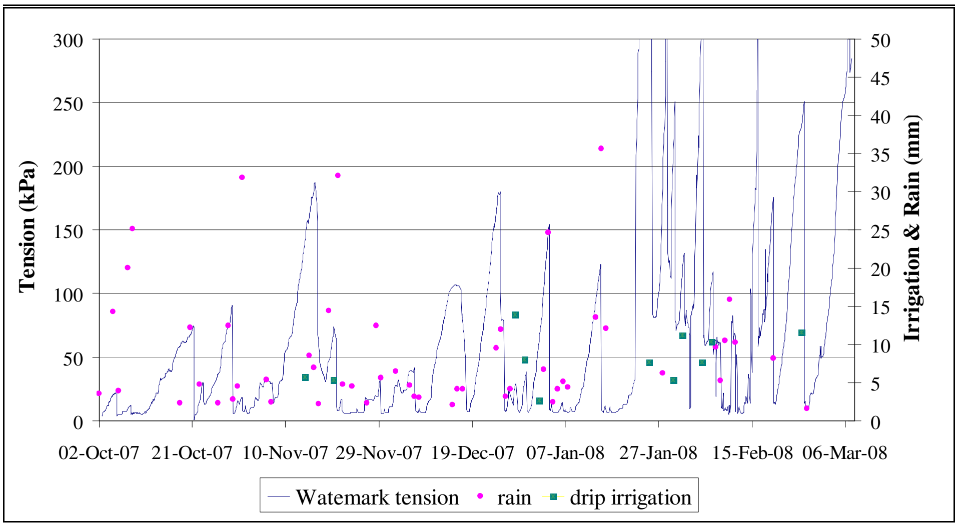

Figure 4.8 Soil water tension at Drip Watermark 3 to rainfall and irrigation events

Due to the various limitations with the number of watermark sensors available, results were inconclusive as to whether either irrigation treatments showed superior soil moisture results. Significantly more assessment locations would be required to give a conclusive analysis. However, the main focus of the watermark analysis was to assess if the resultant trends obtained from the watermark analyses correlated with the results obtained from the irrigation scheduling program, SA*sched*. This is done for Furrow C in Figure 4.9, with the soil moisture content scale inverted, with drier soil at the top for easier comparison with the tension. Although different units are used to measure the outputs from the soil moisture monitoring and the irrigation scheduler, both outputs indicate trends that the soil is drying out over the monitoring time period.

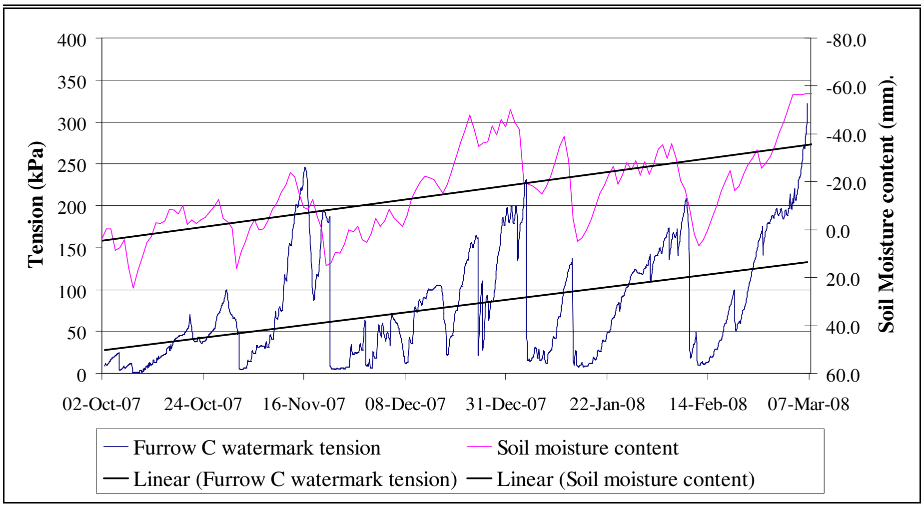

Figure 4.9 Trends in Furrow C's water tension and SA*sched* predicted soil moisture content

The soil moisture predicted, using SA*sched* for the ASFI and SSD irrigation treatments, are illustrated in Figure 4.10. The SSD irrigation treatment received slightly less irrigation during August due to problems with holes in the drip tape. However, this was countered in September with the SSD irrigation treatment receiving additional irrigation than the ASFI trial. This would most likely have minimal impact on the harvest results. According to SA*sched*, both irrigation methods managed to avoid plant water stress. The plant stress used in SA*sched* is based on the reference evaporation which was generally between 2 mm to 4 mm for the Ukulinga trial, which is low for a sugarcane production area. If the reference evaporation was higher, say 6 to 8 mm, then the plants would have experienced stress. The plant water stress level in Figure 4.10 is for the drip plot, which is very similar to the plant water stress level for the ASFI plot.

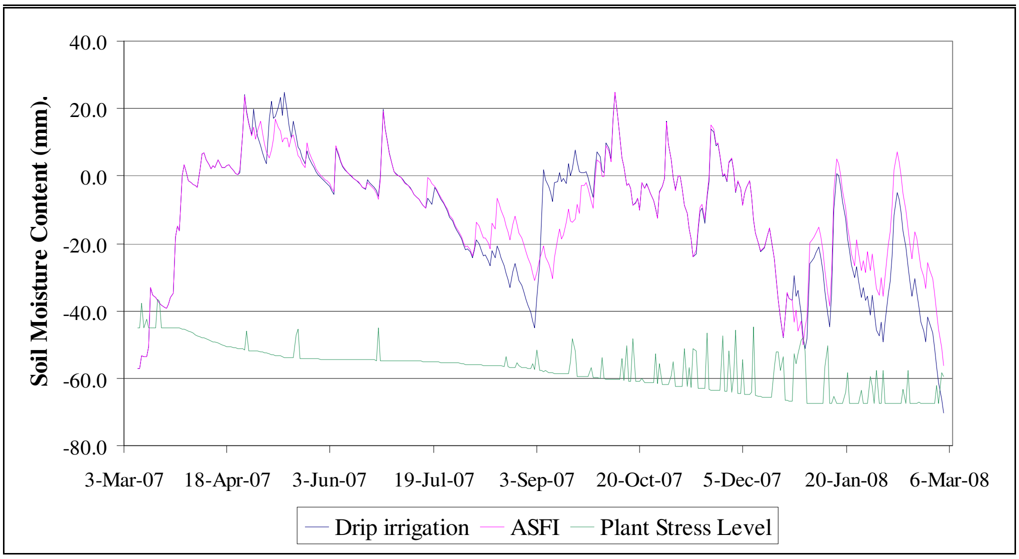

Figure 4.10 SA*sched* predicted soil moisture for the ASFI and drip irrigation plots

The cumulative irrigation of the SSD irrigation and the ASFI treatment are shown in Figure 4.11. Initially, the SSD irrigation treatment received approximately 50 m^3 cumulative irrigation or 20 mm more water. Towards the end of the cycle, the ASFI system received slightly more water, approximately 20 mm more, due to valve and system testing and field demonstration days. This was not necessarily beneficial to the plant as there were significantly more irrigation events for ASFI line 1 than ASFI Line 2. These tests were also for a shorter time periods than the regular cut-off time of 40 minutes, resulting in a larger amount of water being applied to the beginning of the furrow.

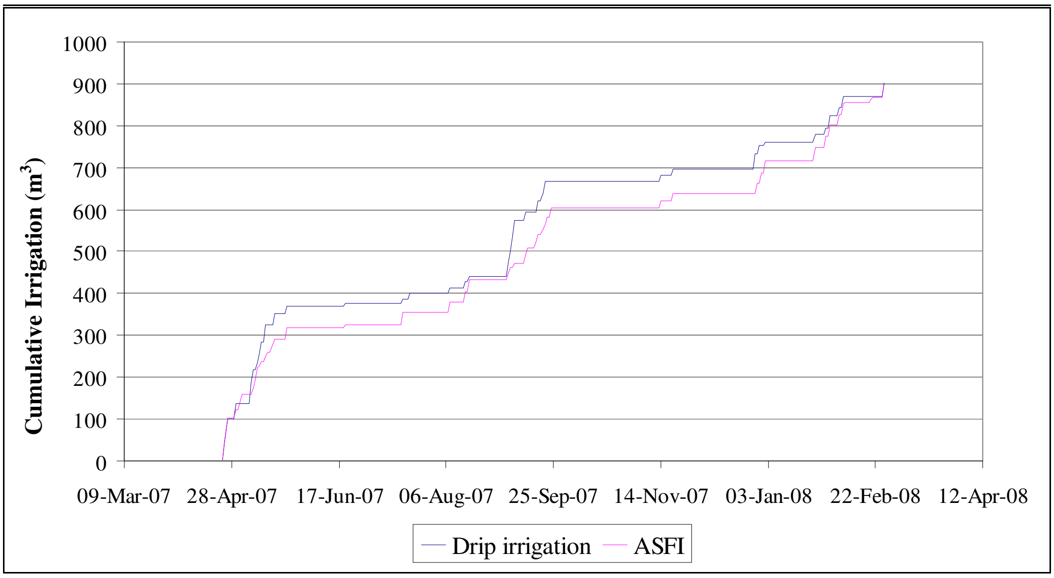

Figure 4.11 Cumulative Irrigation for the Drip Irrigation and ASFI plots

The irrigation performance analysis and soil moisture analysis were the first two major facets of the comparative performance analysis of the two irrigation treatments. Comparing the soil moisture analysis results of the two treatments proved to be inconclusive due to the limited resources and natural variability in soil conditions. The irrigation performance analysis proved that in the trial, the drip irrigation treatment had superior uniformity results to the ASFI treatment. However, it is important to assess if this had any impact on the crop yields. This formed the final major facet of the comparative analysis.

4.4 Crop Yields

A major agronomic consideration was the impact of the different irrigation systems on crop yields. However, a number of factors during the course of the trial may have affected the results. The first factor was the gap filling. However, the sections without sugarcane, which required gap filling, were measured and found to be approximately equal for both systems. The second factor is that Nitrogen fertigation only commenced late and hence the yield could be influenced by the natural variability in soil nitrogen. As an indication of the possible yield, SA*sched* predicted a yield of approximately 90 tons/ha for both systems.

The total weights for each row for the ASFI and drip irrigation treatments are shown in Tables 4.15 and 4.16 respectively. The total weight of each row was divided by the row area, with measurements in kg/m^2. This was then converted to tons/ha. From the sucrose sampling, the total weight of the stalks after topping and trashing was divided by the total weight of the cane before trashing and topping. This resulted in a field average fraction of 0.7653 representing the weight of the clean stalks to the weight of the stalks together with tops and trash. The total weight (t/ha), the weight of stalk with tops and trash per hectare, was then multiplied be the 0.7653 fraction to obtain the stalks weight (t/ha), the weights of stalk without tops and trash per hectare.

The harvest results show an average of 129.2 tons cane/ha for the total ASFI area and an average of 123.6 tons cane/ha for the total drip irrigation area. The ASFI area therefore had a slightly higher tons cane/ha. The tons per hectare for each row and for the plot average are recorded in Tables 4.15 and 4.16 for the ASFI and SSD plots respectively.

Table 4.15 Harvest results for the ASFI area

Row	**Total (kg)**	**L (m)**	**Total Weight (t/ha)**	**Stalk Weight (t/ha)**	**Row**	**Total (kg)**	**L (m)**	**Total Weight (t/ha)**	**Stalk Weight (t/ha)**
B2	857.5	29.65	160.67	122.96	**D2**	1073.5	29.50	202.17	154.72
B3	787.8	29.40	148.86	113.92	**D3**	1009.0	29.55	189.70	145.18
B4	883.0	29.70	165.17	126.40	**D4**	979.0	29.30	185.63	142.06
B5	813.8	29.50	153.25	117.28	**D5**	857.0	30.00	158.70	121.46
B6	764.0	29.30	144.86	110.86	**D6**	798.4	29.90	148.35	113.53
		Ave:	154.56	118.29			**Ave:**	176.91	135.39
G2	979.5	29.55	184.15	140.93	**I2**	853.0	29.20	162.29	124.20
G4	934.0	28.90	179.55	137.41	**I4**	869.2	28.60	168.84	129.21
G6	852.0	30.05	157.52	120.55	**I6**	793.6	28.60	154.16	117.98
G8	1135.0	29.80	211.60	161.93	**I8**	818.5	28.55	159.27	121.89
G10	965.3	29.30	183.02	140.07	**I10**	829.2	29.05	158.58	121.36
		Ave:	183.17	140.18			**Ave:**	160.63	122.93

Table 4.16 Harvest results for the drip area

Row	**Total (kg)**	**L (m)**	**Total Weight (t/ha)**	**Stalk Weight (t/ha)**	**Row**	**Total (kg)**	**L (m)**	**Total Weight (t/ha)**	**Stalk Weight (t/ha)**
C2	899.8	29.50	169.44	129.68	**E2**	893.8	29.60	167.75	128.38
C3	779.0	29.15	148.47	113.62	**E3**	772.8	29.35	146.27	111.94
C4	902.8	29.00	172.94	132.35	**E4**	822.3	27.25	167.64	128.29
C5	847.5	29.90	157.47	120.51	**E5**	589.5	27.50	119.09	91.14
C6	659.2	29.80	122.89	94.05	**E6**	706.0	24.60	159.44	122.02
		Ave:	154.24	118.04			**Ave:**	152.04	116.35
F2	916.8	30.05	169.49	129.71	**H2**	950.5	29.30	180.22	137.93
F4	785.0	30.00	145.37	111.25	**H4**	835.5	29.35	158.15	121.03
F6	986.5	30.10	182.08	139.34	**H6**	951.0	29.75	177.59	135.91
F8	1037.8	30.20	190.90	146.10	**H8**	947.0	29.45	178.65	136.72
F10	774.5	30.15	142.71	109.22	**H10**	922.5	29.45	174.02	133.18
		Ave:	166.11	127.12			**Ave:**	173.73	132.95

Although the stalk weight (t/ha) for the ASFI trial was higher, it was necessary to assess if the difference was statistically significant. A one-way ANOVA using JMP Software (SAS Institute inc., 2008) was used on the stalk weight (t/ha) yield and the sucrose (t/ha), in Figures 4.12 and 4.13 respectively. In the Ukulinga trial, there was no significant difference in the results obtained and therefore, it cannot be concluded that either system performed better with regard to yield and sucrose yield results.

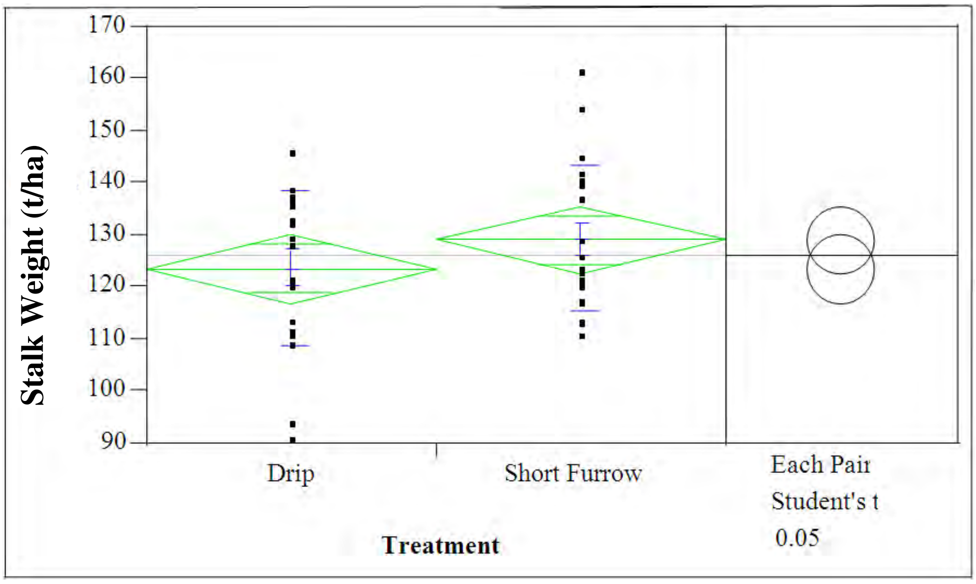

Figure 4.12 One-way analysis of stalk yield (t/ha) by treatment. The middle of the green diamond represents the mean of the values for each treatment. The vertical span of the diamond represents the 95 % confidence interval for each group.

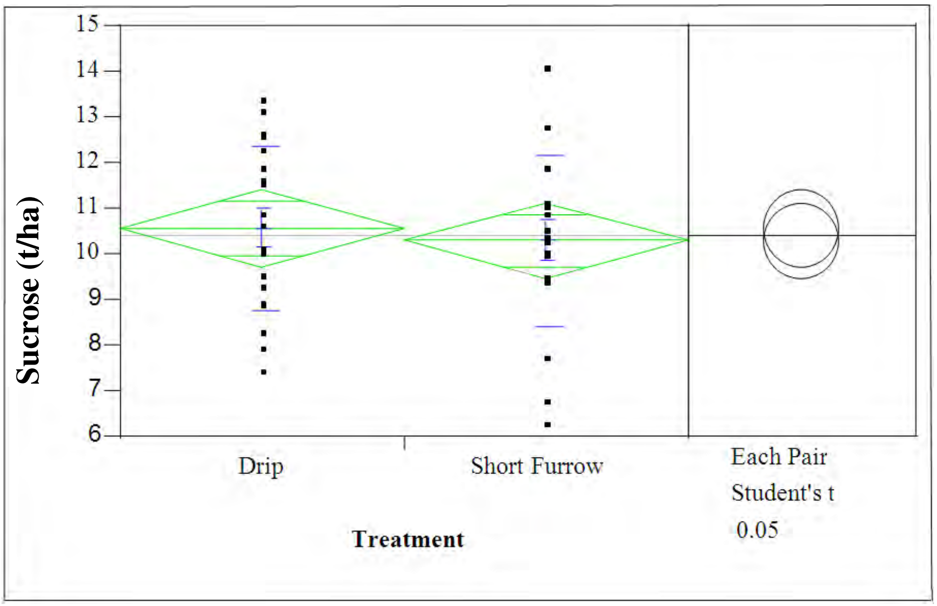

Figure 4.13 One-way analysis of the sucrose yield (t/ha) by treatment. The middle of the green diamond represents the mean of the values for each treatment. The vertical span of the diamond represents the 95 % confidence interval for each group.

The photo in Figure 4.14 was taken in plot B with the crop height being an average height for the field. Crop height varied from about 2 m in the small region of poor growth in plot B as a result of low Nitrogen levels, to just over 3.5 m in other locations in the field.

Figure 4.14 Average crop heights

4.5 Re-establishment

As a result of the harvesting operation, the repair of certain drip lines and furrows was necessary. During the course of the crop cycle, repairs to the drip tape were necessary due to cuts while weeding and from rodent bite marks. These were repaired, but not re-buried to the required depth. During the harvesting operation both the bell loader, used to lift the sugarcane out of the field and place the sugarcane on a trailer, and the grab for the weighing device shown in Figure 3.26, tended to pull the drip lines out. This resulted in the drip lines stretching. Approximately 30 % of the drip lines required replacing or repairs. As a result, a large portion of the cane was manually carried to the furrow plots as it was easier to grab with the bell loader. The bell loader did, however, affect some of the furrow shapes. The furrow shaper was therefore used to reshape the furrows in Plot G and Plot I. The furrows in Plot B and Plot D were left without reshaping. Ideally a bell loader should not be used during the harvesting process of ASFI. An implement known as a Bell All Terrain Vehicle (ATV) would be better–suited, as this vehicle does not need to turn in the field and can therefore drive parallel to the furrows so that the furrows would not require reshaping between the crop ratoons.

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The third project goal was to: assess the performance of the ASFI system relative to a reference drip irrigation system by evaluating agronomic, economic and engineering considerations. The major test results are included in Chapter 4. The first test was on the boot and piston valve which was able to operate within the pressure range that would be used for ASFI. However, a larger, injection moulded, valve would significantly reduce the pressure loss through the valve, allowing for more consistent pressures down the mainline or sub-main. The next tests were the irrigation performance tests where the SSD irrigation treatment tests produced a higher *DU* of approximately 90 %, as opposed to the 72 % to 80 % for the ASFI treatment. The next step was to assess whether the differences in *DU* impacted the soil moisture results and the crop yield results. Due to the limited number of watermark sensors, the soil moisture analysis using watermark sensors was inconclusive as to whether either irrigation system obtained better soil moisture trends. The soil moisture analysis did, however, indicate that SA*sched*, the irrigation scheduling tool, accurately predicted the trends in soil moisture. The results from SA*sched* indicate that both irrigation treatments resulted in no crop stress. The yield analysis on both the crop yield and the sucrose yield was insignificant according to the one-way statistical analysis conducted on the results. The agronomic and engineering considerations (the irrigation performance analysis, soil moisture analysis and the crop yield analysis) are contained in Chapter 4. The economic considerations are included as a consideration for large-scale applications of ASFI in Chapter 5.

5. CONSIDERATIONS FOR LARGE-SCALE APPLICATIONS OF ASFI

The major reasons for incorporating Chapter 5 in this dissertation was firstly, to include an economic comparison of ASFI and SSD irrigation, and secondly, to incorporate the lessons learnt during the field trial in recommendations for the large-scale application of ASFI. The ASFI design is included in a cost comparison with the SSD irrigation design to assess the economic feasibility of ASFI. The cost comparison between the ASFI and SSD systems was not conducted on the Ukulinga trial as this would bias the results against the SSD system, which required significantly more laterals than normal with the short (30 m) plots. The major consideration when designing the large-scale ASFI system was to assess various layout configurations to achieve a system which results in the optimum combination regarding performance and economic feasibility.

The system performance was examined as it was essential to optimise the system prior to completing an economic analysis. SIRMOD III simulations were run using the soil characteristics from the Ukulinga trial and practical constraints such as cut-off time. The optimum combination of inputs was then determined using the CE discussed in Chapter 2.1. However the major factor in evaluating the system performance is the robustness to change. High *DU*s of above 90 % are possible for each option investigated, which makes the robustness of the various furrows to change the major performance factor. Due to the valve being able to accurately control the cut-off time, the cut-off time will not be altered to assess robustness. The system sensitivity to variation was therefore checked by altering the furrow slope, altering the flow-rate and altering the soil conditions. Three furrow lengths of 29.2 m, 33.9 m and 40.2 m were selected for the sensitivity analysis, as these furrow lengths allowed a 400 m field to be broken down evenly into furrow sets with a spacing of 30 cm between each furrow set, as discussed in Section 5.4.1.

5.1 Sensitivity to Slopes

It was determined during the Ukulinga field trial that, theoretically, the flatter the furrow slope, the more uniform the irrigation application. If a slope could be accurately levelled to

1:1000, this would produce an extremely uniform and robust system. However, it is extremely difficult to obtain the preciseness required to ensure that this slope is achieved during land-levelling. Practically, with a 1 cm height difference over a 10 m length for the 1:1000 slope, any slight ridge in the furrow would significantly reduce the uniformity of the irrigation event. It was thus decided to select a slope of 1:250 for the sensitivity analysis as this slope would be steep enough, so that a slight ridge would not significantly affect the performance, yet flat enough, so that a highly uniform irrigation event is possible. A slope of 1:250 is a typical slope for conventional furrow irrigation.

From output simulated using SIRMOD III, it was found that the three furrows with various lengths (29.2 m, 33.9 m and 40.2 m) are all robust to a variation in furrow slope from the design 1:250 slope. Note that the other variables, such as flow-rate, were not optimised for each slope, but kept constant at the optimum value for the 1:250 slope. The accompanying changes to *DU* are illustrated in Figure 5.1. The various furrow lengths are all robust, producing *DU*s of above 85 % for a furrow slopes ranging from 1:150 to 1:500. Slight infield slope variability will therefore, theoretically, have minimal impact on the performance of each of the furrow lengths. The system's robustness to slope variation will allow for a practical design layout with consistent furrow spacing when contour furrows are used. Ensuring correct slopes are achieved is probably easier for the shorter furrow lengths, as land levelling is required over shorter stretches.

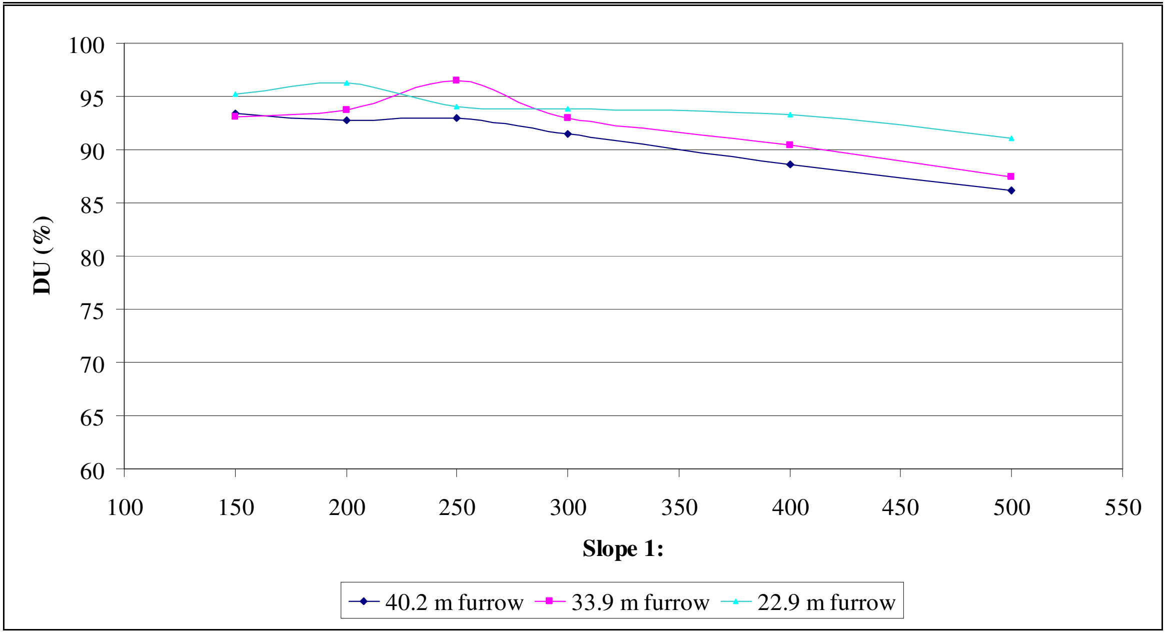

Figure 5.1 Sensitivity of ASFI to variation in slope on DU

5.2 Sensitivity to Flow-rates

SIRMOD III simulations were performed with the flow-rate being altered from the design value and with all other variables, such as slope, kept constant. The accompanying changes in *DU* are shown in Figure 5.2. The optimum flow-rate was decreased by 1 l/min, 2 l/min and 3 l/min for each furrow length. The optimum flow-rate was also increased by 1 l/min, 2 l/min, 3 l/min and 4 l/min. All three furrows are more sensitive to a decrease in flow-rate. The 40.2 m furrow is slightly less sensitive to a change in flow-rate, than the other furrow lengths. Increasing the flow-rate by 4 l/min did, theoretically, still result in a highly uniform application of above 80 % for each of the furrow lengths. It would therefore be advisable to design the flow-rate slightly above the initial flow-rate to enable the system to be more robust.

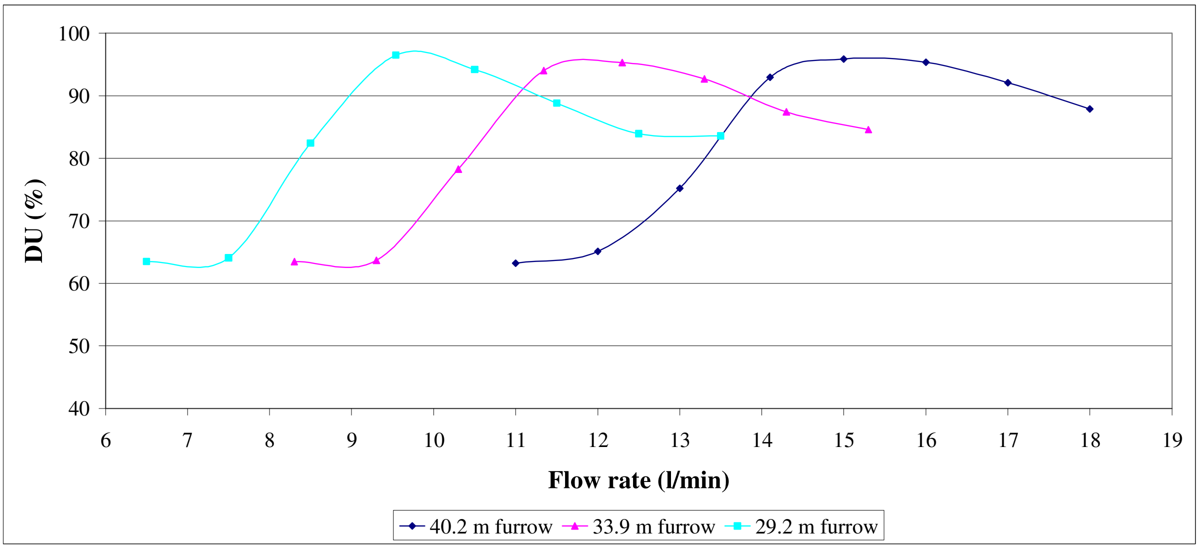

Figure 5.2 Sensitivity to flow-rate variation from the designed flow-rate on system performance with a slope of 1:250

5.3 Sensitivity to Soils

The two major soil considerations are the soil wetness variability and soil type variability. Variation in the soil wetness, at the start of the numerous irrigation events during the course of the year, is inevitable. However, it is optimal to attempt to maintain the soil water deficit between 20 mm and 30 mm, as discussed in Section 3.4.1. Figure 5.3 contains the results of the cumulative infiltration for the tests conducted on Furrow 1 in the trial during the course of the year. The variation is mainly due to the variation in soil moisture for each test. The four B5 curves grouped closely together are the curves for the Furrow test. The curve which is second from bottom is the curve from the initial Ukulinga test, the test that will be used in this sample design. The Furrow 1 cumulative infiltration curves are very similar, although there is a variation in the soil water of approximately 24 mm between the various irrigation events. This would be a likely soil moisture variation in practise. Therefore, soil moisture variation is relatively insignificant in an optimally designed system. However, to ensure minimal variation in the soil moisture, it is advisable to use an irrigation scheduling tool such as SA*sched*. The generic clay and silty clay loam cumulative infiltration curves are included in Figure 5.3 as a guide when visually comparing the results of the Furrow B5 cumulative infiltration curves to the various soil infiltration curves in Figure 5.4.

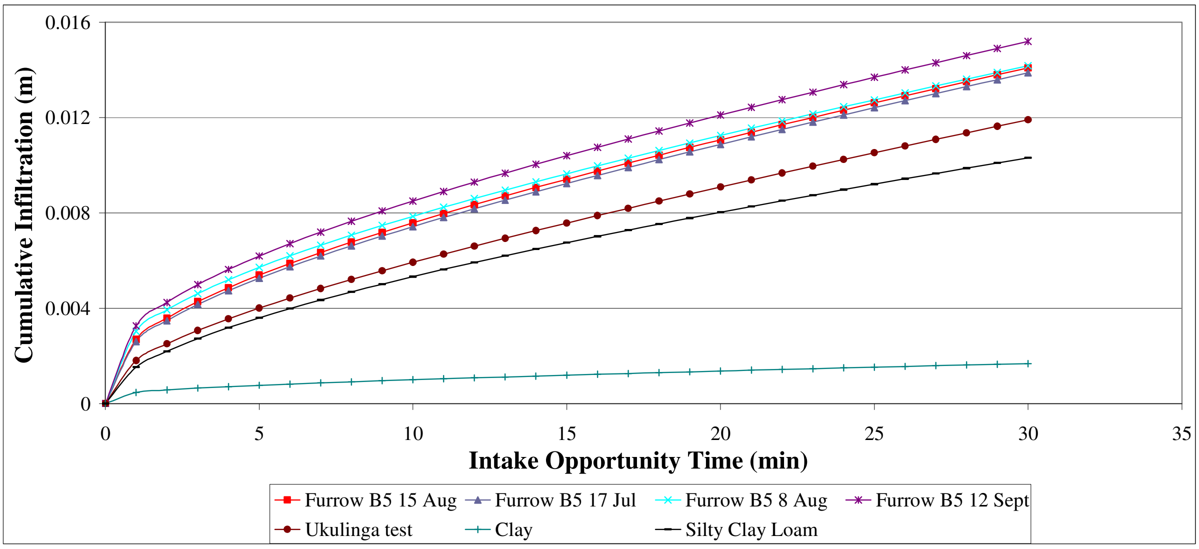

Figure 5.3 The effect of soil moisture variation on the cumulative infiltration and therefore system performance

Figure 5.4 contains the cumulative infiltration curve of the Ukulinga test furrow in conjunction with the cumulative infiltration curves simulated by SIRMOD III for various soil types. The Ukulinga test soil infiltration lies between a silty clay loam and a clay loam. On a small-scale of approximately one hectare, as used in the trial, soil variation is normally relatively small. However, on a larger scale, soil type variability can become more significant.

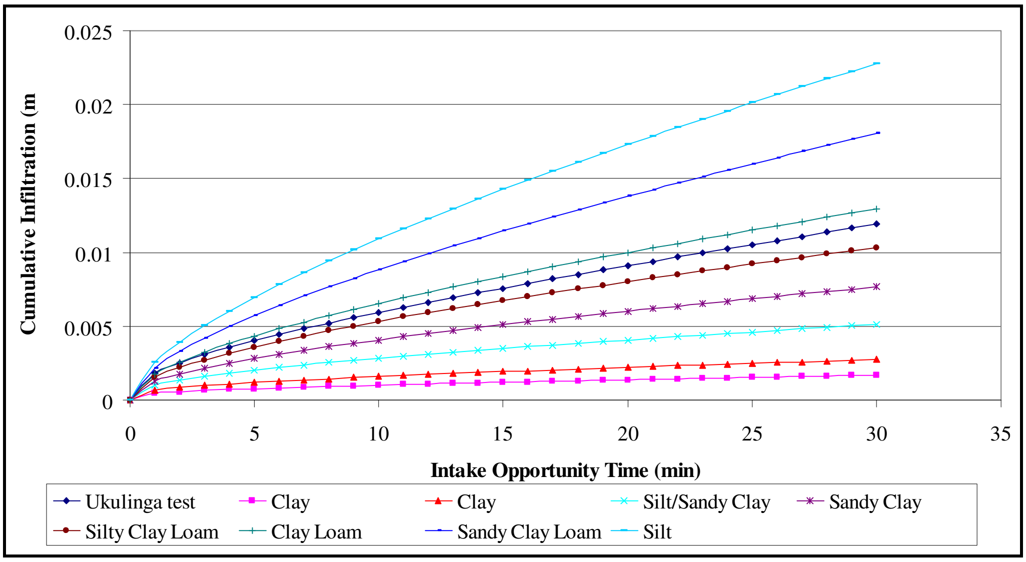

Figure 5.4 Comparison of the cumulative infiltration of the Ukulinga test to various soil types

SIRMOD III simulations indicate that the system is sensitive to a variation in soil types when the inflow-rate and cut-off time is kept constant, as illustrated in Figure 5.5. It is therefore necessary to analyse a possible range in soil type to assess the sensitivity of the various furrow lengths to a soil change. Ideally, a soil map of the area would give a range of soil types present. This could be analysed and test furrows could be placed in each soil type area. The flow-rate and irrigation time could then be altered for the various soil type areas to ensure a uniform water application. When comparing the various furrow lengths to a change in soil type, it appears that the shorter furrows are, theoretically, less sensitive to a variation in soil type. Fields where there are variable soil types may not be suited to ASFI.

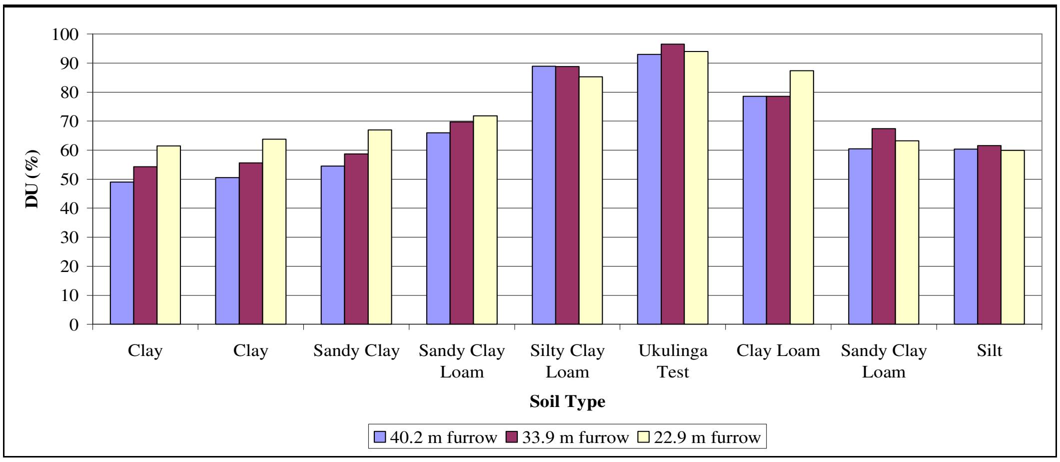

Figure 5.5 Sensitivity to soil type variation from the designed soil on the system performance with a slope of 1:250

5.4 Economics

Each of the furrow length options in Sections 5.1 to 5.3 was deemed to be theoretically robust. The 22.9 m furrow appeared to be the most robust. It is also necessary to assess the costs of each of the furrow length options, as shorter furrows would result in more laterals. However, the lower flow-rate as a result of the shorter furrows results in the pipe sizes of the laterals being smaller. If is therefore necessary to carry out designs for each of the 3 furrow length options to assess which option is economically optimal. A representative ASFI field is required.

5.4.1 Representative ASFI design and costs

For the representative ASFI design, a relatively flat, ten hectare section of land was assumed. The field width, as illustrated in Figure 5.6, was assumed to be 250 m with a natural slope of 1:250. Furrows are assumed to be along the width of the field at a furrow spacing of 1.8 m, with laterals down the length of the field. The field length was assumed to be 400 m with a slope of 1:50. A maximum allowable irrigation time of 22 hours was selected to allow for breaks due to interruptions in the power supply. A GIR of 5 mm/day was used with a 2-day irrigation cycle, which results in a required irrigation depth of 10 mm.

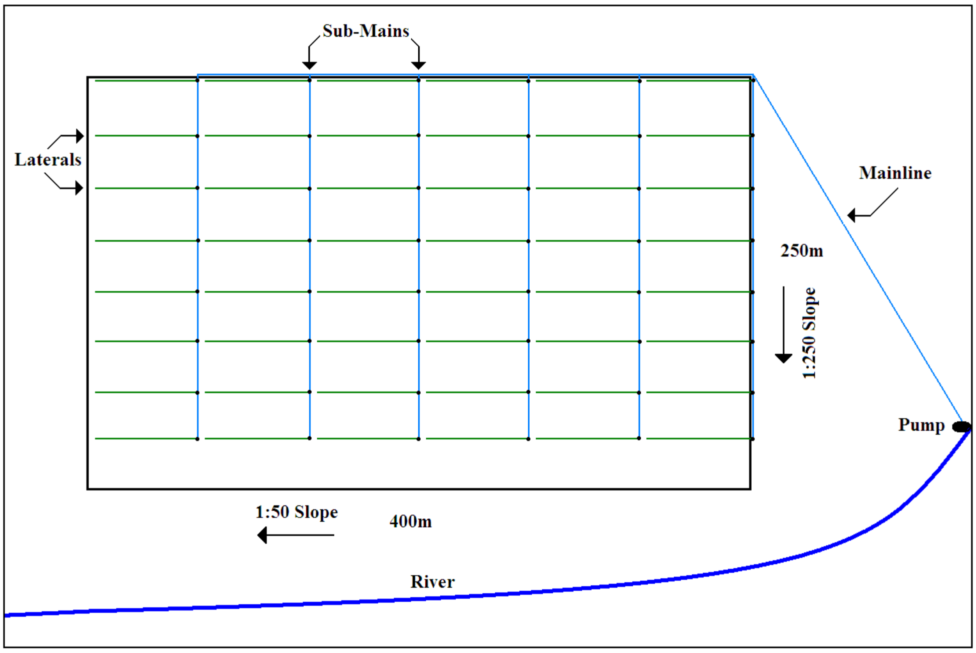

Figure 5.6 Representative ASFI field layout

The 3 furrow length options used in Sections 5.1 to 5.3 were then included in the economic analysis to assess which furrow length was the most economically suitable option. The field width was divided up into blocks with equal furrow lengths, with a spacing of 30 cm between the end of one furrow and the start of the next, allowing space for the blocked end of the one furrow and the emitter of the next furrow. The number of plots was then calculated by multiplying the number of laterals by the number of sub-mains.

The next objective was to determine irrigation options in which the total irrigation time/day was as close to the maximum irrigation time as possible, namely 22 hours/day. Pumps can therefore run almost permanently, reducing the size of the pump required and therefore reducing the energy requirements. Pipe sizes can also be reduced, as lower flows are required when irrigating over longer periods. The objective is to therefore find an inflow-rate and irrigation time/plot combination which could operate as close to the maximum irrigation time/plot and minimum inflow-rate as possible, while still producing a highly uniform and efficient irrigation event. Each of the scenarios in Table 5.1 was for irrigating one block at a time. The soil used for the designs was assumed to be the same as the soil used in the initial Ukulinga tests. On larger fields, it is possible that 2 or more furrow sets could be irrigated simultaneously. The calculations in Table 5.1 are used to determine options with a high *DU* while utilising the maximum irrigation time. Each of the scenarios in Table 5.1 was tested in SIRMOD III with notes discussed after Table 5.1

Table 5.1 Possible combinations of furrow length and slope to determine the most suitable option

Test No.	Furrow length (m)	Lateral Length (m)	No. of plots	Max. time/plot (minutes)	Min inflow-rate (l/min)	Note
1	40.17	66.67	36	73.33	9.86	Too slow
2	33.91	66.67	42	62.86	9.71	Too slow
3	29.15	66.67	48	55.00	9.54	Option 1
4	40.17	57.14	42	62.86	11.50	Too slow
5	33.91	57.14	49	53.88	11.33	Option 2
6	29.15	57.14	56	47.14	11.13	Too quick
7	40.17	50.00	48	55.00	13.15	Option 3
8	33.91	50.00	56	47.14	12.95	Too quick
9	29.15	50.00	64	41.25	12.72	Too quick

Where: Maximum irrigation time = total available time (22 hours x 2 days)/ no. of plots.
Irrigation Volume = furrow spacing x furrow length x required depth.
Minimum Inflow-rate= Irrigation Volume (L) / Max. irrigation time.

SIRMOD III simulations indicated the first two tests in Table 5.1, which used 6 sub-mains each, resulted in the application rate being too slow with deep percolation at the start of the furrow and insufficient water at the end of the furrow. This could be overcome by increasing the flow-rate, however this would result in a significantly decreased irrigation time. This would mean that the full 44-hour cycle time would not be used. The system flow-rate would therefore be significantly higher than it should be, which would result in higher capital and operating costs as a result of larger pumps and pipelines required. The third test in Table 5.1 produced a *DU* of 94 % with minimal changes required to the irrigation time and inflow-rate. The third test was therefore the first possible option, Option 1, which has 8 laterals on each sub-main.

Simulations were then run with 7 sub-mains for Tests 4 to 6. This resulted in a lateral length of 57.14 m. Test 4 produced a flow-rate that was too slow. Test 5 produced a *DU* of 96.5 % with minimal changes to the irrigation time and inflow-rate. This therefore became another option for the system, Option 2. Option 2 has 7 laterals on each sub-main. Test 6 produced a flow-rate that was too quick, resulting in deep percolation at the end of the furrow and insufficient irrigation at the start of the furrow.

Simulations were then run with 8 sub-mains for tests 7 to 9. Test 7 was selected as Option 3 with a *DU* of 81 %. Unlike Options 1 and 2, Option 3 required slight adjustments to the flow-rate to achieve the highest possible theoretical *DU* with the other variables such as slope, soil type and cut-off time set, as discussed in this Chapter. A flow-rate of 14.1 l/min produced the highest *DU* of 93 % for the furrow length of 40.17 m and was therefore used as Option 3b in Table 5.2.

Table 5.2 Theoretical *DU* values for the furrow length and flow-rate combination for Options 1, 2 and 3

Option	**Furrow Length**	**Flow-rate**	**Irrigation time**	**DU**	**Comment**
	(m)	(l/min)	(min)	(%)	
1	29.15	9.54	55	94.03	Approximately Optimum
2	33.19	11.33	53.88	96.47	Approximately Optimum
3	40.2	13.15	55	81.07	Increase flow-rate slightly
3b	40.2	14.1	53	92.94	Nearly Optimum

The laterals were then designed for the three options. The spreadsheets used, based on the Darcy Weisbach friction equation (ARC, 2003), were too large to be included in the document, but are found on the accompanying CD as an Excel file named "Sample_design". A 65 mm pipe was used as the maximum lateral pipe diameter due to the lower costs associated with LDPE pipe (as opposed to HDPE and PVC pipe), with common LDPE pipe sizes being up to 65 mm. The goal of the lateral design is to achieve relatively consistent pressures in the lateral by adjusting pipe sizes down the lateral. This will allow emitter pipes to be of similar length, simplifying the installation process, yet still achieving consistent flow-rates through each emitter.

As stated previously in the Chapter, system costs and system performance were the two criteria used to determine the most suitable furrow length option. The cost comparison entailed assessing the 3 options, with the possible savings in, for example, the lateral costs, being offset by the increased sub-main costs. For example, the longer the laterals, the larger the diameter of the sub-mains needs to be, yet fewer sub-mains will be required. It is therefore necessary to design the laterals as well as the sub-mains for each of the options, to determine the pipe sizes and hence the cost. Fortunately, the field slope was consistent throughout the field for this example and therefore only one lateral and one sub-main needed to be designed for each option. The details of the design calculations for the lateral and the sub-main are given as an Excel file named "Sample_design" on the accompanying CD. The final piping requirements and costs for the lateral are listed in Table 5.3. The piping requirements and costs for the sub-main are in Table 5.4. The prices used for Low Density Poly Ethylene (LDPE) pipe were obtained from PipeFlo (2007).

Table 5.3 Lateral piping (Class 3 LDPE) requirements and costs for various options

Option	Pipe Size (mm)	No. of Sections	No. of Lats.	Pipe Length Req. (m)	Piping Required (m)	Cost/m (R)	Cost (R)
Option 1	25	1	48	86.4	100	3.19	319.00
	32	3	48	259.2	300	4.42	1326.00
	40	4	48	345.6	350	6.29	2201.50
	50	7	48	604.8	650	10.17	6610.50
	65	22	48	1948.8	1950	15.50	30225.00
					Total Cost:		**40682.00**
Option 2	40	7	49	617.4	650	6.29	4088.50
	50	6	49	529.2	550	10.17	5593.50
	65	19	49	1724.8	1750	15.50	27125.00
					Total Cost:		**36807.00**
Option 3	40	4	48	345.6	350	6.29	2201.50
	50	7	48	604.8	650	10.17	6610.50
	65	15	48	1344.0	1500	15.50	23250.00
					Total Cost:		**32062.00**

Table 5.4 Sub-main piping (Class 3 LDPE) requirements and costs for various options

Option:	Pipe Size (mm)	pipe length/ sub-main (m)	No. of Sub-mains	Piping Required (m)	Cost/m	Cost (R)
Option 1	80	220.8	6	1350	12.31	16618.50
Option 2	80	216.1	7	1542	12.31	18982.02
Option 3	80	209.8	8	1704	12.31	20976.24

The total lateral and sub-main piping costs were then calculated with Option 1 costs being R57 300.50, Option 2 costs being R55 789.02 and Option 3 costs being R53 038.24. Option 3 was marginally the most economical option, for the quoted pipe costs. The mainline costs for each option were identical due to the similar flow requirements for each option. These costs are included later in the chapter. The connectors were not included in these calculations but will be included in the final design as they do not have a significant impact on the cost comparison. Due to the minimal variation in costs of the three options, Option 1 was selected as it was the best option in terms of system performance as discussed in Sections 5.1 to 5.3.

The main objective of the economic analysis was to compare the costs of a representative ASFI system to the reference drip irrigation system. Land-levelling or smoothing costs are dependent on the field conditions and were therefore not included in the hardware costs, as there could be a large variation in these costs due to variation in factors such as field location and the cut and fill requirements. All types of irrigation systems would most likely require some degree of land forming for surface drainage purposes. The high precision smoothing needed for ASFI may, however, add to the initial land preparation costs, relative to other systems. The system piping costs, as well as trenching costs, are shown in Table 5.5. The trenching costs, at R6.50 per metre, form a major portion of the system costs as ASFI requires a large amount of piping due to the small plot sizes. The design for the sample 10 ha system used only LDPE pipe. PVC pipe could have been used for the sub-main and main line if the total cost, including transport, results in the PVC being more economical. Further investigation into piping options may yield a more optimum system and result in substantially reduced costs. For example, so-called storm-water pipe is relatively low-cost at R17/m for 110 mm diameter pipe and it may be suitable for ASFI, even though it does not have a pressure rating.

Table 5.5 Sample design piping costs

Piping costs	**Quantity (m)**	**Cost [R]**
Lateral Pipes		
25 mm LDPE	100	143.00
32 mm LDPE	300	729.00
40 mm LDPE	350	1176.00
50 mm LDPE	650	3640.00
65 mm LDPE	1950	15697.50
Sub main Pipes		
LDPE 80 mm	1350	16618.50
Main line Pipes		
LDPE 65 mm	30	241.50
LDPE 80 mm	1103.5	15485.86
Trenching	5833.5	37917.75
Total costs for:	Piping + trenching	91649.11

Pipe fittings are a minor cost in the system, whereas the major cost, shown in Table 5.6, is the cost of the valves. The valve price is estimated at R 650 per valve, which would most likely be reduced if the valve went into mass production. The rest of the pipe fittings are relatively insignificant in terms of system economics.

Table 5.6 Sample design pipe fittings and extras costs

Pipe fittings & extras costs	**Quantity**	**Cost [R]**
Lateral extras		
32-25 mm nylon reducer	48	181.67
40-32 mm nylon reducer	48	222.16
50-40 mm nylon reducer	48	288.37
65-50 mm nylon reducer	48	889.20
Hose Clamps	384	1 152.00
Sub main extras		
80 mm nylon couplings	35	602.00
Hose Clamps	100	350.00
Mainline extras		
80 mm nylon couplings	30	516.00
80-65 mm reducers	1	17.10
Hose Clamps	70	245.00
Valve costs	48	31 200.00
Total costs for:	Extras	35 663.51

The selected pump was a KSB ETA 40-160. This pump has an efficiency of 62 % for the flow-rate and head required for the sample design. A quote for the pump was obtained, as in Table 5.7, as a total pump assembly cost from Armitage *et al.* (2008). A 50 ha ASFI system would have a similar pump station to a 50 ha drip system. As the 10 ha ASFI system was being compared to a 50 ha drip irrigation system, the cost of the drip irrigation pump station was divided by 5, so that the costs/ha of the pump station were equal.

Table 5.7 Sample design pump and pump station costs

Pump and pump station costs		**Cost [R]**
Total pump assembly		19 655.00
Pump station		9609.40
Total costs for:	Pump+station	29 264.40

5.4.2 Representative sub-surface drip design and costs

A representative 50 ha drip system completed by *Zululand Irrigation* and obtained from Armitage *et al.* (2008), was used in the economic comparison with the 10 ha sample ASFI system. The drip design is not included in this dissertation, but the costs will be used in the life cycle comparison in Section 5.4.3.

5.4.3 Life cycle comparison

The next step was to determine the life cycle costs for the 10 ha ASFI system and the 50 ha SSD design completed by ***Zululand Irrigation*** and used in Armitage *et al.* (2008). This was done using the software tool, Irriecon V2 (Armitage *et al.*, 2008). Tables 5.8 and 5.9 are a summary of the costs for 5 mm/day ASFI and 5.83 mm/day drip irrigation systems respectively. The values for the insurance, maintenance, salvage value and expected life were obtained from Oosthuizen *et al.* (2005). The maintenance value and expected life of the ASFI valves were estimated based on experience gained in the Ukulinga trial. The trenching costs were not included in the ASFI Irriecon costing and the costs of burying the drip lines were not included in the drip irrigation Irriecon costing. Although burying the ASFI pipes is optimal, it is not essential, as pipes could be laid on the surface and removed during harvesting. The drip irrigation system requires a filter, which the ASFI system does not. The major cost component of the drip system is the drip lines.

Table 5.8 Summary of the costs of the 5 mm/day 10 ha ASFI system.

	Cost (R)	**Insurance (%)[1]**	**Maintenance (%)[2]**	**Salvage value (%)[3]**	**Expected life (yrs)**
Piping	53 732		0.2	30	20
Valves/fittings	35 663		1.5		10
Pump+station	29 264	0.83	2	15	15
Sub total	118 659				
Total per ha	**11 866**				

[1&3] *– % of Purchase Price*

[2] *– % of Purchase Price/1000 hours per year*

Table 5.9 Summary of the costs of the 5.83 mm/day 50 ha Drip system.

	Cost (R)	Insurance (%)[1]	Maintenance (%)[2]	Salvage value (%)[3]	Expected life (yrs)
Mains & sub-mains	219 892		0.2	30	20
Filter station	83 633		5	0	10
Pump & station	48 047	0.83	2	15	15
Drip lines	507 263			0	7
Sub- total	858 833				
Total per ha	**17 177**				

[1&3] – % of Purchase Price
[2] – % of Purchase Price/1000 hours per year

Table 5.10 contains a summary of the ASFI and drip irrigation system inputs. As a result of the pump for the drip system being larger, the network charge for the pump has a higher tariff.

Table 5.10 Summary of irrigation system inputs for the different irrigation systems and irrigation strategies used in Irriecon V2

	SSD 5.83 mm/1 day	**ASFI 10 mm/2 days**
Electricity		
Basic charge (R/month)	R 192.30	R 192.30
Network charge (R/month)	R 310.80	R 202.20
Energy charge (R/kWh)	R 0.3028	R 0.3028
Absorbed power (kW)	23.9	2.3
Power factor of the motor (h)	0.9	0.9
Pump rate design value (m^3/hr)	120.0	21.8
Water		
Water charge (c/m^3)	3.44	3.44
Other		
Irrigated area (ha)	50.0	10.0
Labour hrs/24hr irrigation period	3.2	3.2

A comparison of annual irrigation costs between the 5 mm/day ASFI system and the 5.83 mm/day SSD irrigation system on a cost per hectare basis is contained in Table 5.11. Mainline costs include the pump and pump station, all piping (excluding drip lines) and the filter (for the drip irrigation system). The mainline fixed costs are significantly higher for the ASFI system due to a larger number of laterals for the smaller plot sizes. The mainline operating costs are mainly the electricity costs for the pump, which are slightly higher for the drip system due to the larger pumping head requirements. The mainline operating costs also include the mainline maintenance costs, with the filter maintenance and repairs being relatively large. The system fixed costs are the cost of the drip laterals for the drip irrigation system and the costs of the valves for the ASFI system. The drip lateral costs are the major expense of the drip system. Although 48 valves are required for the 10 ha ASFI system, this does not translate to a high cost over the valve's life span. The system variable costs are the water costs, the labour costs and the repair and maintenance of the drip laterals and valves. The system variable and mainline operating costs may be slightly biased against the drip system due to the slightly higher daily irrigation requirements, 5.83 mm/day as opposed to 5 mm/day for the ASFI system, as electricity and water charges will be increased slightly. The mainline fixed costs will probably not be affected as the difference in irrigation requirements between the two systems is unlikely to affect the pump and pipe sizes.

Table 5.11 Comparison of irrigation costs between the ASFI and drip irrigation design

	Drip	**ASFI**
IRRIGATION COSTS (R)	**5.83 mm/l day cycle**	**10 mm/2 day cycle**
Mainline costs		
Mainline fixed costs	808.17	1 207.02
Mainline operating costs	479.55	283.59
Total mainline costs	1 287.72	1 490.61
System costs		
System fixed costs	1,819.64	485.35
System variable costs	539.91	352.03
Total system costs	2 359.55	837.38
Total irrigation costs	**3 647.28**	**2 268.63**

5.5 Design Considerations

The 10 ha field size is approximately the upper limit for irrigating one plot at a time. On a larger scale, two or more plots will be irrigated simultaneously. These plots will be on different sub-mains to reduce the flow requirement of the sub-main. For a small-scale field of below 7 ha, if the water source is not gravity fed, the pump will run for a portion of the day.

Soil type is an important consideration. The results from the SIRMOD III simulations placed the Ukulinga trial plot soil between a silty/sandy clay and a silty clay loam, as shown in Figure 5.4. Preliminary investigations were run on SIRMOD III to assess the performance and robustness for a range of designed soil types. It must be noted that a robust system with good uniformities and efficiencies, is possible for the complete range of soil types using ASFI. If the designed field has a soil with high sand content, preliminary SIRMOD III simulations indicate that shorter furrow lengths of approximately 20 m would be optimal. However, the flow-rate into the field will need to be increased slightly, with a shorter cut-off time. On a soil with high clay content, there are two design solutions that produced high efficiencies and uniformities. The first solution is to keep short furrows, but to ensure that these furrows are extremely flat. The water will then rush to the end of the furrow and then pond all the way back to the start of the furrow. However, this requires precise land-levelling. The second solution is to increase furrow lengths (up to 200 m for soils with extremely high clay contents), depending on the soil type. The flow-rate will generally be decreased and the cut-off time increased. The decreased flow-rate will allow longer laterals to be used. The long laterals and furrow lengths will result in significantly less piping being required and hence, reduced costs.

Field slopes also affect the design. The field used for the 10 ha ASFI design was on a relatively flat slope. The furrows were run down a gentle slope or on the contour and the laterals were therefore run down the steepest slope. If the field slope was steeper, lateral sizes could be decreased as the pressure loss through the lateral would negate the height difference.

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Although an analysis of the considerations for large-scale applications of ASFI was not one of the project goals, this was necessary to perform an economic comparison between ASFI and the reference drip system. The 5 mm/day ASFI system was considerably more cost-effective than the 5.83 mm/day drip system, although this was in part due to the slightly higher SSD irrigation requirements (5.83 mm/day). The final project goal was partially addressed in Chapter 5.5 with recommendations for the application of ASFI. However, this will be addressed in more detail in Chapter 6, along with recommendations for future research.

6. DISCUSSION AND CONCLUSIONS

ASFI is an irrigation system whereby irrigation water is sequentially supplied to sets of short furrows using an automatic control valve as part of a pipe network. The hypothesis that ASFI could be a valuable irrigation method, was based on the following premises:

- ASFI has low energy requirements which could reduce pumping costs, compared to systems such as SSD and sprinkler irrigation. With only 5 to 10 m pressure required at the field edge, there could be increased opportunities for gravity driven, automated systems.
- ASFI potentially has low capital costs due to relatively low-cost, low pressure piping requirements.
- ASFI can potentially be robust and produce a highly efficient and uniform irrigation application due to accurate control through the automated valve.

The project objective was, therefore, to develop and evaluate a novel, automated system for short furrow irrigation. The four major tasks set to meet the main project objective were:

- to conduct a theoretical analysis of ASFI in the context of other irrigation systems and the identification of design requirements and design tools (Chapter 2);
- to design and commission a prototype ASFI system for sugarcane in a field trial, including furrows, pipe network and a novel, automatic control valve to facilitate the operation of the system (Chapter 3);
- to assess the performance of the ASFI system relative to a reference drip irrigation system by evaluating agronomic, economic and engineering considerations. These included: irrigation performance tests, soil moisture monitoring analysis, a yield analysis of the harvested crop and an economic comparison of ASFI and SSD irrigation systems (Chapters 4 and 5); and
- to make recommendations for the application of ASFI and further research and development (Chapters 5 and 6).

The major findings in meeting the tasks are elaborated in Sections 6.1 to 6.4, according to the chronological implementation and testing procedure used in the Ukulinga trial. This is followed by project conclusions and recommendations for further development.

6.1 Site Establishment

The first major facet of site establishment is land levelling/smoothing, where the field would either be levelled to a slope of approximately 1:250, or smoothed and the furrows run along the contours at slopes between 1:150 and 1:500. In theory and based on simulations with SIRMOD III, flatter slopes perform well and are more robust, but in practice, flatter slopes need precise levelling otherwise the relatively small flows used in ASFI could be negatively affected or even stopped by small undulations in the furrow. For the Ukulinga trial, no levelling equipment was available and the furrows were constructed along the length of the field with a furrow slope of approximately 1:40, to simplify the design, layout and machinery operation. The steeper than optimal furrow slopes were accepted for two main reasons, namely:

- the fields were not properly levelled, so steeper slopes ensured less chance for blockages in the furrows; and
- it was a research project and the impact of having steeper than ideal slopes could therefore be investigated.

Using slopes of 1:40 is not recommended for further installations of ASFI. Not only are the robustness and uniformity of the irrigation events compromised, but also large irrigation events tend to move towards the end of the furrow, resulting in a higher infiltration at the end of the furrow. These steep slopes may also result in the irrigation applications causing erosion in the furrow for certain soil types.

In the Ukulinga trial, the irrigation furrow was constructed using a ridger (pig’s ear) to open up the furrow, followed by a curved steel pipe to press, compact and smooth out any soil clods. This did not smooth the furrow sufficiently. It is recommended that instead of the steel pipe, a press wheel should be located just behind the ridger to smooth the furrow. An irrigation furrow was constructed every 1.8 m along the width of the field to comply with tractor tyre spacing, with a planting row on either side of the irrigation furrow spaced 60 cm apart. It is recommended that when using sugarcane as the crop, the plant spacing should be increased to 70 to 80 cm to reduce the potential for seed cane to be displaced during the construction of the irrigation furrow.

6.2 Irrigation Design

The evaluation component of the SIRMOD III simulation software was used in the design and analysis of the test and trial furrows. In an investigation of the sensitivity of ASFI to various factors using SIRMOD III, the furrow irrigation performance was found to be most sensitive to a decrease in the furrow inflow-rate. Thus, when designing an ASFI system, the furrow inflow-rate should be set slightly higher than the optimum value to accommodate variations in flow-rate. Simulations showed that ASFI could effectively irrigate a wide range of soil types. While a furrow length of 30 m was shown to be suitable for a wide range of soils, optimum furrow lengths could be reduced to 20 m for very sandy soils with high infiltration rates, and extended to up to 200 m for heavy clay soils with very low infiltration rates. Fields with highly variable soil types would require a more intricate design and could result in factors such as furrow inflow-rate and furrow lengths differing in different sections of the field. Ideally, test furrows should be constructed in the various soil type regions throughout the field. Approximately 10-15 irrigation events should then be run over a few days to smooth the furrow out. In preparation for the recorded advance/recession front tests, the furrows should then be left for approximately 2 days in a planted field or 4 days in an uncultivated field, to allow for the soil moisture to reduce to a level when irrigation events would take place in practice. The performance of the ASFI system is only one component of the field layout, and system costs and practicality also need to be considered. A practical furrow layout uses long planting/field lengths divided into the required, shorter sections. Machinery will therefore be able to drive down a number of sets of furrows approximately 30 m long before turning around.

An LDPE pipe network was selected for the Ukulinga trial as LDPE is extremely cost-effective in the smaller diameter pipe sizes (65 mm or less). LDPE also has the added benefit of being more UV resistant than PVC and can be laid on the surface. In practice, this piping could be buried or rolled up and removed from the field when required, for example, during harvesting operations. However, it is unlikely that the emitter to lateral connections would survive repeated handling. PVC is more cost-effective in the larger pipe sizes and better suited to the mains and sub-mains. There is potential to develop or trial, low-cost piping options that would be suitable for the low pressure requirements of ASFI. Standard PVC irrigation pipes have a pressure rating of 40 m or greater, which is excessive for ASFI. ASFI operates with pressures of less than 10 m. The use of movable laterals, such as quick coupling HDPE pipe, is an option which may render the system very cost-effective and is worth investigating.

The aim of the Ukulinga ASFI design for Lines 1 and 2 in Figure 3.14 was to ensure consistent pressures along the pipeline so that equal lengths of 10mm diameter polypipe could be used for the emitters. However, there is still the potential that the flow-rate from the emitters of equal length may vary slightly due to slight pressure variations in the lateral. If the flow-rate from an emitter was notably below the designed value, this would result in poor uniformities. It is recommended that a low pressure flow controller is developed to attach to the end of the emitter to regulate the flow-rate from each emitter. Emitter flow controllers would also be advantageous if there were different supply pressures to the various laterals in a field, and using the flow controllers would simplify the design and installation procedures.

An advantage of ASFI is that because the *DUs* are good, fertigation is possible, which is particularly beneficial in a tall crop such as sugarcane. In the Ukulinga trial, a venturi combined with a flow controller was used to supply the fertiliser into the irrigation water. This would not be optimal in most ASFI systems, as the venturi requires a large pressure difference across a point such as a flow control valve, which would require a higher supply pressure and have subsequent increased pumping costs. An improved fertigation method would be to use a fertiliser injector to supply the fertiliser to the system at a constant rate without pressure losses, which is required in ASFI to ensure an even fertiliser distribution.

In a large-scale ASFI pipe network, control valves are required, firstly, at the connection point from the mainline to the sub-mains, and secondly, at the connection point from the sub-mains to the laterals. It is recommended that a manual gate valve should be used to control flow off the mainline into the sub-main and that the automatic boot and piston valves should be used to control the flow to each lateral down the sub-mains. As the boot and piston valve is difficult to override, if there is a power outage midway through a cycle, the irrigation event could be controlled using the gate valve to continue from the approximate point where it was discontinued. The focus of the sub-main design is to obtain relatively consistent pressures down the sub-main so that each lateral is supplied at similar pressures. The major pressure loss down the sub-main is through the automatic control valve.

6.3 The Automatic Control Valve

The focus of the valve development was to obtain a valve that would adequately meet the requirements for the Ukulinga trial which were to control the flow of water in two directions (firstly down the lateral and secondly, down the mainline) for a specific time interval. There were still a few issues with the boot and piston valve that were identified during the Ukulinga trial and a subsequent analysis of potential improvements to the valve was conducted. Firstly, there were high pressure losses through the Ukulinga boot and piston valve (approx. 1-1.5 m at an inlet pressure of 5 m). The pressure losses could be reduced either by using a larger valve, or by using a more compact injection moulded design to reduce the number of bends. The friction loss through the valve is directly proportional to v^2, where v is the velocity through the valve (m/s). Therefore, a reduction in the velocity through the valve could result in a significant reduction in head loss through the valve.

For the Ukulinga trial, a 50 litre tank was used as a timing chamber. For further use of the valve, it is recommended that a section of large piping be used as the timing chamber to reduce costs. A pressure release valve (PRV) was used in the Ukulinga trial to release air from the tank and to shut when the water reached the top of the timing chamber. However, the PRV tended to leak. This could be overcome with further development and refinement of the PRV. It is also recommended that a small finger filter could be fitted to the bleed tube to prevent debris from clogging the bleed tube. This would be self cleaning as it would be situated in the pipeline.

One of the advantages of the boot and piston valve is that there are no electrical parts, which reduces the probability of theft and eliminates the requirement for electricity at the numerous valve locations. A problem with the Ukulinga boot and piston valve was that the valve had external moving parts which, if interfered with by livestock or machinery, may result in the valve malfunctioning. An improvement to the valve would therefore be to house the boot in an internal chamber. Although there were no problems with the boot, using a rubber diaphragm to move the piston, as used on standard valves, could also be investigated as a potential improvement. The Ukulinga boot and piston valve accurately controlled the irrigation events for approximately 1 year, with no visible damage or wear and tear.

6.4 ASFI in the Context of Other Irrigation Systems

ASFI will not outperform all other irrigation systems in all circumstances, but definitely has advantages over other irrigation systems in a variety of situations. After running numerous simulations, implementing the Ukulinga trial and completing a cost analysis on a sample large scale ASFI design, ASFI can be described as a system which has:

- low energy requirements compared to systems such as SSD and sprinkler irrigation, with energy requirements similar to conventional surface irrigation with 5 to 10 m pressure required at the field edge;
- low capital costs relative to a drip irrigation system due to cost-effective, low pressure piping; and
- a high degree of robustness when correctly designed and installed, being able to produce a highly efficient and uniform irrigation application due to accurate control through the automated valve, as well as having balanced discharges through proper hydraulic design of the water supply system, and the use of short furrows.

ASFI is well suited to flat terrain, land with a gravity supply of water and as a replacement for surface irrigation systems where the supply restrictions and the field layout result in poor uniformities and large losses due to deep percolation. ASFI should also be considered in situations where surface irrigation is used on shallow soils. On steeper land, where furrows run along the contours, there are concerns that furrows may break during large rainfall events. However, if the system is correctly installed with adequate attention to surface drainage and waterways, ASFI may actually help reduce erosion, as each furrow acts like a small contour bank.

The optimum application depth for ASFI is approximately 10 – 20 mm, depending on the soil depth. ASFI potentially has less evaporation than drip irrigation, which applies smaller irrigation depths of approximately 5mm on a daily basis, resulting in the soil surface being consistently wet which may increase the potential for evaporation. ASFI potentially also has less evaporation losses than sprinkler and centre pivot irrigation as only a very small portion of the soil surface is wetted.

The performance of the ASFI system was assessed relative to a reference drip irrigation system as part of the Ukulinga trial. This included: irrigation performance tests, a soil moisture monitoring analysis, a yield analysis of the harvested crop and an economic comparison of ASFI and SSD irrigation systems.

6.4.1 Irrigation performance tests

From the numerous furrow tests on the selected furrows, the Ukulinga ASFI system produced a *DU* of 72 % to 80 %. This excludes the results from the 15 August 2007 test on ASFI line 2, with *DU*s of between 58 % and 75 %, as the emitter problem was an isolated incident which should have been rectified prior to the installation of the irrigation system. The *DU* results of between 72 % and 80 % were high relative to the results from experiments conducted by Reinders (2001) on sprinkler and micro irrigation systems (Section 2.4), despite the furrow slope being significantly steeper than optimum (1:40 as opposed to 1:250). For the SSD tests conducted on 21 May 2008, *DU* results of 90 % to 91 % were obtained for randomly selected drip laterals. These high *DU* results are contrary to what was visually observed, with holes on laterals that were not selected for the drip tests resulting in significant over-watering in the surrounding area. If the laterals with holes had been randomly selected for the test, the results could have been significantly different.

6.4.2 Soil Moisture analysis

SA*sched* was a simple, accurate and important irrigation scheduling/management tool for both the Ukulinga ASFI and drip irrigation treatments. SA*sched* is recommended for irrigation scheduling in the South African climate. Watermark sensors are recommended when assessing trends in soil moisture and when comparing differences in soil moisture at different locations. However, watermark sensors are inaccurate in dry conditions. For the Ukulinga trial, the watermark sensors were used along with Hobo loggers to assess trends in soil water tension and to compare the trends with those predicted by SA*sched* for soil moisture. Both the watermark soil tension results and the SA*sched* soil moisture results followed similar trends and it was therefore assumed that SA*sched* was sufficiently accurate for scheduling.

It was also envisaged that the watermark sensors could be used to analyse differences in trends between the ASFI and SSD soil moisture tension. However, upon analysing the results, it became apparent that the localised soil and rooting conditions substantially affected the absolute soil water tension readings. Considerably more measuring locations in the plot would be required to ascertain if there was a soil moisture difference between the ASFI and SSD irrigation methods at specific locations, relative to the furrow/lateral and the crop. There were no conclusive differences between the trends in soil water tension of the two irrigation methods.

In the Ukulinga trial, faulty connections caused problems with the Hobo data-logger and watermark sensors. Subsequent to the trial, the Chief Technician at UKZN has developed an improved connector.

6.4.3 Yield analysis

Although the *DU* results from the irrigation performance tests were noticeably lower for the ASFI system than the drip system, this had no significant impact on both the cane and sucrose yield results. According to a one-way statistical analysis on cane and sucrose yield, there was no significant difference between the two irrigation treatments for near equal amounts of water. This result is positive, as the ASFI irrigation performance could be significantly improved by, among other things, using more gradual slopes. This could result in improved yields under the ASFI system. However, crop growth may have been dependant on the natural nutrients of the virgin land, as the first application of fertiliser was extremely late, namely 10 months after planting. The late fertiliser application may, therefore, have negated any potential variation in the yield results. The Ukulinga trial is in an area with high rainfall relative to the irrigation requirement. It is recommended that a drier region should be selected for future comparisons of the ASFI and SSD systems

6.4.4 Economic analysis

The aim of conducting the Ukulinga trial was to compare the performance of the ASFI and reference drip systems. The trial layout was selected accordingly. System costs for the irrigation systems used in the trial were therefore not considered representative of systems that would typically be used in practice. Sample irrigation designs were developed for both the drip and ASFI systems. The lifecycle costs of each system were determined using a software tool known as Irriecon V2. The ASFI sample design was designed for the purpose of this study and the drip design was conducted by *Zululand Irrigation* as reported in Armitage *et al.* (2008). Unfortunately, these two designs were conducted simultaneously and were therefore designed with slightly different irrigation requirements. The 50 ha drip design had an irrigation design application amount of 5.83mm/day and cost approximately R3 650/ha according to a lifecycle analysis using Irriecon V2. The 10 ha ASFI design had an irrigation design application amount of 5 mm/day and cost approximately R2 300/ha according to a lifecycle analysis using Irriecon V2. The ASFI system was designed for a field which required water to be pumped. In a situation where the scheme is gravity fed, both the operating and capital costs would be less.

The sample ASFI system was cheaper than the sample drip system. However, there are three issues that could/would reduce the cost difference. The first issue is that the system variable and mainline operating costs will be slightly biased against the drip system due to the slightly higher daily irrigation design application amount, as electricity and water charges will be increased slightly. The mainline fixed costs will probably not be affected as the difference in irrigation requirements between the two systems is unlikely to affect the pump and pipe sizes. The second factor is that the cost of land preparation was not included. Both irrigation systems require land smoothing/forming. It is likely that the ASFI would require greater precision in land smoothing/levelling, which would increase the lifecycle cost/ha slightly, depending on the available resources to the farmer. The third issue is that, for both the ASFI and SSD systems, trenching and burying of drip lines were not included in the economic analysis. Adding the trenching costs to the ASFI system would substantially increase the capital cost of the system due to the amount of pipe required. With an assumed trenching cost of R6.50/m, the capital costs of the 10 ha sample design would increase by approximately R38 000. To reduce capital costs, it is recommended that the LDPE sub-mains are left on the surface and the laterals are buried. This would not limit machinery operation in the field as the sub-mains run parallel to the furrows.

6.4.5 Labour and maintenance requirements

For the Ukulinga trial, the irrigation installation was slightly more labour-intensive for the SSD irrigation system, as the laterals were laid by hand. However, on a larger scale, the ASFI installation is likely to be slightly more intensive than other irrigation systems due to the large number of pipes that require installation. If furrow lengths vary along a lateral, the installation process for ASFI is likely to be even more intensive as emitter pipes would have to be cut to different lengths along the lateral, to obtain the optimum flow-rate and the required irrigation depth.

In the initial stages after installation, the Ukulinga ASFI system was more labour-intensive than the Ukulinga drip system, as problems with specific furrows needed to be corrected. However, most of these problems were due to the Ukulinga ASFI system layout and inadequate land preparation. After the initial stages, the Ukulinga drip irrigation system had a higher labour requirement as the dripper lines needed to be flushed and holes in the dripper lines needed to be repaired, whereas the Ukulinga ASFI system required mainly supervision. From the sample design in Section 5.4.1, the maximum area from which one lateral can be irrigated at a time is 10 ha. For larger areas, two or more laterals could be irrigated simultaneously. The main irrigation task for the labourer would be to ensure that the valve does not malfunction and that emitters are correctly positioned. It is unlikely that one labourer would be able to check on two laterals concurrently. Therefore the labour requirements for ASFI would be about one labourer per 10 ha. Conventional systems such as drip and dragline sprinkler require one labourer for every 20-25 ha (ARC, 2003). However, the labour for the conventional systems would be focussed solely on tasks such as moving sprinkler stands or flushing drip laterals. The ASFI labourer would be able to do tasks such as weeding, as the irrigation requirements for the labourer are only supervisory. Therefore, the total labour required, for say a 100 ha drip/dragline system, would be similar to the labour requirement for a 100 ha ASFI system.

6.5 Project Conclusions

The postulated hypothesis that ASFI has the potential to be a robust, relatively low-cost system with a highly uniform and efficient irrigation application is confirmed. However, this will require further tests and developments. *DU*s of 80 % to 95 % are possible if the system is designed and laid out correctly. ASFI is still in the developmental phase, and there will most likely be reduced capital and operating costs and a simplified design with the continued development of the system. The focus of the Ukulinga trial was on the development of a complete ASFI system and not on the optimisation of the individual system components, such as the valve. Based on the above, it is concluded that the project objective, to develop and evaluate a prototype automated system for SFI, was met. The prototype system was used to grow a crop of sugarcane and in terms of yield and water use, there were no significant differences between the prototype ASFI system and the benchmark SSD system. The first 3 tasks to achieve the project objective where achieved in Chapters 2, 3 and 4 respectively. Recommendations for the application are included in Chapter 6, with the only incomplete task being the recommendations for further research and development It is recommended, to achieve this task, that the next step in the development of the system should be to design, install and test a large-scale ASFI system on 10 ha or more.

7. REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. *Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No. 56, FAO, Rome, Italy.

Allen, RG. 1999. Instructions for attaching soil water resistance blocks to the Onset Hobo H-08 4-Channel External Soil Moisture Logger (or the single channel data Hobo logger). [Internet]. University of Idaho. Kimberly, USA. Available at: http/:www.kimberly.uidaho.edu/water/swm/WM_Hobo2.htl. [Accessed: 19 October 2009].

Anon. 2003. Information Sheet 7.9: Leaf Sampling. In: *Sugarcane Agricultural Course Notes*. South African Sugarcane Research Institute, Mt. Edgecombe, RSA.

Anon. 2005. Information Sheet 13.18: Variety N31. In: *Sugarcane Agricultural Course Notes*. South African Sugarcane Research Institute, Mt. Edgecombe, RSA.

ARC. 2003. *Irrigation Design Manual*. ARC – IAE, Pretoria, RSA.

Armitage, RM, Lecler, NL, Jumman, A and Dowe, K. 2008. Implementation of the *Irriecon* V2 decision support tool to assess net returns to irrigation systems. *Procedures of the South African Sugar Technologists Association,* 81: 454-465.

ASAE Standards, 50th Ed. 1997. EP458. Field Evaluation of Micro-irrigation systems, ASAE, St. Joseph, USA.

Ascough, GW. 2005. *Deliverable 2: Interim Report on Standardised Terminology and Essential Variables or Factors*. Report No. 2:K5/1482/4. WRC, Pretoria, RSA.

Austin, C. 2003a. Micro Flood. [Internet]. Waterright, Melbourne, Australia. Available from: www.waterright.com.au [Accessed on 2 August 2004].

Austin, C. 2003b. Making the Most of Water- Micro Flood Operating Manual. [Internet]. Waterright, Melbourne, Australia. Available from: www.waterright.com.au [Accessed on 2 August 2004].

Austin, C. 2003c. Micro Flood Video. [Internet]. Waterright, Melbourne, Australia. Available from: www.waterright.com.au [Accessed on 2 August 2004].

Badenhorst, JW, de Lange, M, Mokwena, ME and Rutherfoord, RJ. 2002. Water Conservation and Water Demand Management in Agriculture: Development of Water Management Plans by Irrigation Water Suppliers in South Africa. *Eighteenth*

Congress, Montreal, Canada. International Commission on Irrigation and Drainage, New Delhi, India.

Basset, DL, Fangmeier, DD and Strelkoff, T. 1980. Hydraulics of surface irrigation. In: ed. Jensen, ME, *Design and Operation of Farm Irrigation Systems.* Monograph 3, 447-498. ASAE, St Joseph, Michigan, USA.

Booher, LJ. 1974. *Surface Irrigation*, FAO of the United Nations, Rome, Italy.

Brouwer, C, Prins, K, Kay, M, and Heibloem, M. 1988. Furrow Irrigation. In: *Irrigation Management: Irrigation Methods*, Ch. 3. Food and Agricultural Organization of the United Nations. Rome, Italy.

Burt, CM, Clemmens, AJ, Strelkoff, TS, Solomon, KH, Bliesner, RD, Hardy, LA, Howell, TA and Eisenhauer, DE. 1997. Irrigation Performance Measures: Efficiency and Uniformity. *Journal of Irrigation and Drainage Engineering* 123 (November/December): 423-442.

Cain, J. 2001. *Planning Improvements in Natural Resources Management.* Centre for Ecology and Hydrology, Wallingford, UK.

Crosby, CT, de Lange M, Stimie, CM and van der Stoep I. 2000. *A Review of Planning and Design Procedures Applicable to Small-Scale Irrigation Projects*. Report No. 578/2/00. WRC, Pretoria, RSA.

De Lange, M. 1997. Promotion of Low-cost and Water Saving Technologies for Small-scale Irrigation. [Internet]. Available from: http://www.fao.org. [Accessed: 15 February 2006].

DWAF. 2004a. *National Water Resource Strategy*, First Edition. DWAF, Pretoria, RSA.

DWAF. 2004b. *Water Conservation and Water Demand Management Strategy for the Agriculture Sector.* DWAF, Pretoria, RSA.

Fischbach, PE and Goodding, R. 1971. An Automated Surface Irrigation Valve. *Agricultural Engineering*. 52(November): 584-585.

Griffiths, BAK. 2007. In-field Evaluation of Irrigation System Performance within the Sugarcane Industry of the South-East Lowveld in Zimbabwe. Unpublished MScEng Dissertation, School of Bioresources Engineering and Environmental Hydrology, UKZN, Pietermaritzburg, RSA.

Hanson, BR. 2001. Boosting Furrow Systems Uniformity. *Irrigation Journal.* (November/December):16-19.

Henggeler, JC, Sweeren, JM and Keese, CW. 1986. Surge Flow Irrigation. [Internet]. Texas, USA. Available from: www.prsurge.com. [Accessed on 4 May 2005].

Hoffman, GJ, Howell, TA and Solomon, KH. 1990. *Management of Farm Irrigation Systems*. ASAE, St. Joseph, Michigan, USA.

Hornbuckle, JW, Christen, EW and Faulker, RD. 2006. Use of SIRMOD as a Quasi Real Time Surface Irrigation Decision Support System. [Internet]. Australia. Available from: www.mssanz.org.au/modsim05/papers/hornbuckle_1.pdf . [Accessed on 15 June 2007].

Humpherys, AS. 1986. An Automated Single-pipe Irrigation System. *Transactions of the ASAE* 29(1):185-193.

Humpherys, AS, Oest, E and Young, DA. 1983. Spring-operated Semiautomatic Irrigation Valves. *Transactions of the ASAE* 26(1): 134-136, 140.

Humpherys, AS and Stacey, RL. 1975. Automated Valves for Surface Irrigation Pipeline Systems. *Journal of the Irrigation and Drainage Division,* ASCE 101(IR2):95-109.

Jain Irrigation Inc. 2003. Acu-Flo. [Internet]. Jain Irrigation Inc, Fresno, USA. Available from: http://jainsusa.com.s76171.gridserver.com/index.php?option=com_virtuemart&Itemid=247. [Accessed on 29 August 2008]

Jumman, A and Mills, DD. 2005. Tilt Valve for Micro Furrow Irrigation. Unpublished BScEng Design Report, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Kay, M. 1986. Furrow Irrigation. In: *Surface Irrigation Systems and Practice* (Chapter 5). Cranfield Press. Bedford. England.

Koegelenberg, FH and Breedt, HT. 2003. *Manual for the evaluation of Irrigation Systems*. ARC-IAE, Pretoria, RSA.

Koegelenberg, FH and Reinders, F. 2001. *Performance of Drip Irrigation Systems Under Field Conditions*. ARC – IAE, Pretoria, RSA.

Kruger, GHJ. 1998. "*Ontwikkeling en Rekenarisering van 'n Geskikte Vloedbesproiing – Ontwerpprosedure Volume* 2". Report No. 290/2/98. WRC, Pretoria, RSA.

Lecler, NL. 2004a. Performance of Irrigation and Water Management Systems in the Lowveld of Zimbabwe. Unpublished PhD in Engineering. Bioresources Engineering and Environmental Hydrology, UKZN, Pietermaritzburg, RSA.

Lecler, NL. 2004b SA*sched*: A Water Conservation and Demand Management Tool for Irrigated Sugarcane. Paper presented at the South African National Committee on Irrigation and Drainage (SANCID) 2004 Symposium, SANCID, Pretoria, RSA.

Lecler, N. 2005. Personal communication. SASRI, Durban, RSA, 4 May 2005.

Lecler, N. 2006. Personal communication. SASRI, Durban, RSA, 6 April 2006.

Ley, TW. 2003. *Surface Irrigation Systems*. Report No. EM4828. Cooperative Extension-Washington State University, Washington, USA.

Magwenzi, O. 2000. Evaluation of irrigation efficiency in the Swaziland sugar industry. *Procedures of the South African Sugar Technologists Association* 74:151-156.

McClymont, DJ, Raine, SR and Smith, RJ. 1996. The Prediction of Furrow Irrigation Performance Using the Surface Irrigation Model SIRMOD. *13th National Conference-Irrigation Association of Australia*. Adelaide, Australia.

Meyer, WS and Bowmer, KH. 2005. Sustainable Irrigation. In: ed. Bowmer, KH, *Water Innovation: a New Era for Australia*. Ch 4 104-125. CL creations, Adelaide, Australia.

Merriam, J and Keller, J. 1978. *Farm Irrigation System Evaluation: A Guide for Management*. Agricultural and Irrigation Engineering Department, Utah State University, Logan, USA.

Moodley, M. 2001. Effects of Land Disposal of Water Treatment Sludge on Soil Physical Quality. Unpublished PhD dissertation, School of Applied Environmental Sciences. University of Natal, Pietermaritzburg, RSA.

Nishihara, A and Shock, C. 2001. Cost and Benefits of Surge Irrigation. [Internet]. Oregon State University, Oregon, USA. Available from http://www.cropinfo.net/bestpractices. [Accessed on 19 May 2006].

Oosthuizen, LK, Botha, PW, Grove, B, Meiring, JA, Monkhei, MM and Pretorius, IG. 2005. *Cost Estimating Procedures for Micro-, Drip- and Furrow-Irrigation Systems as well as Economic Analyses of the Relevant Irrigation Systems for Large- and Small-Scale Farmers in the Onderberg/Nkomazi Region*. Report No. 974/1/05. WRC, Pretoria, RSA.

Perret, SR. 2002. Water Policies and Smallholding Irrigation Schemes in South Africa: A history and New Institutional Challenges. *Water Policy* 4(3): 283-300.

PipeFlo. 2007. Low Density Polyethylene. [Internet]. Koedoespoort, RSA. Available from: www.pipeflo.co.za/shop/catergory.asp?catid=10. [Accessed on 12 May 2007].

Raine, SR, McClymont, DJ and Smith, RJ. 1997. *The Development of Guidelines for Surface Irrigation in Areas with Variable Infiltration*. National Centre for Engineering in Agriculture, Toowoomba, Australia.

Raine, SR and Walker, WR. 1998. *A Decision Support Tool for the Design, Management and Evaluation of Surface Irrigation Systems*. National Centre for Engineering in Agriculture, Toowoomba, Australia.

Reinders, FB. 2001. *Performance of Irrigation Systems in the Sugar growing Areas of South Africa*. ARC-IAE, Pretoria, RSA.

SAS Institute INC. 2008. JMP®8 Statistics and Graphics Guide. SAS Institute Inc. Cary, NC, USA.

Savva, AP and Frenken, K. 2002. *Irrigation Manual: Planning, Development, Monitoring and Evaluation*. Volume II, Module 7. FAO of the United Nations, Harare, Zimbabwe.

Šimůnek, J, Sejna, M and van Genuchten, M. 1999. The HYDRUS-2D software package for simulating two-dimensional movement of water heat and multiple solutes in variably saturated media. Version 2.0, IGWMC – TPS – 53, International Ground Water Modelling Centre, Colorado School of Mines, Golden, Colorado, USA.

Strelkoff, TS, Clemmens, AJ and Schmidt, BV. 1998. SRFR v 3.31. Computer Program For Simulating Flow in Surface Irrigation, Furrows-Basins and Borders. US Water Conservation Laboratory, Phoenix, Arizona, USA.

Thomson, SJ and Ross, B. 1994. *Using Soil Moisture Sensors for Making Irrigation Management Decisions in Virginia*. Publication 442-024, Virginia Cooperative Extension, Virginia, USA.

Walker, W. 2003. SIRMOD III Surface Irrigation Simulation, Evaluation and Design, User's Guide and Technical Documentation. Utah State University, Logan, Utah, USA.

Walker, W and Skogerboe, G. 1987. *Surface Irrigation Theory and Practice*. Prentice-Hall, New York, USA.

Yonts, CD and Eisenhauer, DE. 2007. *Management Recommendations for Blocked-end Furrow Irrigation*. G1721. University of Nebraska-Lincoln Extension, Nebraska, USA.

8. APPENDIX A

The aim of the irrigation design for both the ASFI and SSD irrigation system was to apply equal depths of water for both systems. From Section 3.3.1, a gross GIR_c of 9.5 mm was calculated and will be used for both systems.

The next step was to determine the lateral emitter flow-rate. A stand time, ts, of 4 hours was selected and the flow-rate from each emitter, q_e was calculated as follows:

$$
\begin{aligned}
q_e &= (GIR_c \times L_d \times L_e) / t_s \\
&= (9.5 \times 1.8 \times 0.5)/4 \\
&= 2.1 \text{ l/h}
\end{aligned}
$$

Where: L_d = distance between dripper lines

L_e = distance between emitters on the dripper lines.

It was therefore decided the Non-Pressure Compensated 2 l/h Netafim Tiran emitters will be used

As there is only one block, the total irrigation time, $t = t_s$. The System flow, Q, was calculated as follows:

$$
\begin{aligned}
\mathrm{Q} &= (\mathrm{GIR_c} \times \mathrm{A_T} \times 10) / \mathrm{t} \\
&= (9.5 \times 0.5 \times 10)/4 \\
&= 11.88 \text{ m}^3\text{/h}
\end{aligned}
$$

The number of emitters per group, n_e, was calculated as follows:

$$
\begin{aligned}
n_e &= 1000 \times Q/q_e \\
&= 1000 \times 11.88/1.9 \\
&= 6253 \text{ drippers}
\end{aligned}
$$

The area per group, A_g, was the calculated as follows:

A_g $= (n_e \times L_d \times L_e)/10000$

$= (6253 \times 1.8 \times 0.5)/10000$

$= 0.56$ ha

Therefore 1 block of 0.5 ha

The drip laterals were then designed with a total of 27 dripper lines on each lateral, 9 laterals in the top half of the field and 18 in the bottom half. The designs for Drip Lines 1 and 2, as shown in Figure 3.14 are on the accompanying CD as an excel spreadsheets named "Drip_design"

The mainline was then designed from Drip line 2 to Drip line 1 using a 40 mm LDPE pipe.

h_f $= 4.516 \times 10^{-10} \times l \times Q^{1.77}/d_i^{4.77}$

$= 4.516 \times 10^{-10} \times (64) \times 3.24^{1.77}/0.040^{4.77}$

$= 1.08$ m

h_1 $= h_2 + h_s + h_f$

$= 10.13 + (3.56\text{-}4.77) + 1.08$

$= 10.00$ m

where: h_1 = pressure at the point where the Drip Line 1 meets the lateral (m),

h_2 = pressure at the point where the Drip Line 1 meets the lateral (m), and

h_s = height difference between the points (m)

The mainline was then designed from Drip Line 1 to the original connection point of Drip Line 0, on the top right of Plot A in Figure 3.14, using a 65 mm pipe. Drip Line 0 was later removed as a result of the gap filling requirements.

h_f $= 4.516 \times 10^{-10} \times l \times Q^{1.77} / d_i^{4.77}$

$= 4.516{*}10^{-10}{*}(64){*}6.48^{1.77}/0.065^{4.77}$

$= 0.36$ m

h_{a1} $= h_{c1} + h_s + h_f$

$= 10.00 + (4.77\text{-}4.55) + 0.25$

$= 10.36$ m

The mainline was then designed from the original connection point of Line 0 to the hydrant using a 40 mm LDPE pipe.

Height of Line 0 start above water hydrant = 2.05 m
Pipe length of hydrant to Line 0 = 45.8 m

$$
\begin{aligned}
H_f &= 4.516 \times 10^{-10} \times l \times Q^{1.77}/d_i^{4.77} \\
&= 4.516 \times 10^{-10} \times (45.8) \times 7.56^{1.77}/0.040^{4.77} \\
&= 3.45 \text{ m} \\
h_{hydrant} &= h_{a1} + h_s + h_f \\
&=10.36 + 2.05 + 3.45 \text{ m} \\
&= 15.86 \text{ m}
\end{aligned}
$$

say 16 m as a result of losses due to bends.

9. APPENDIX B

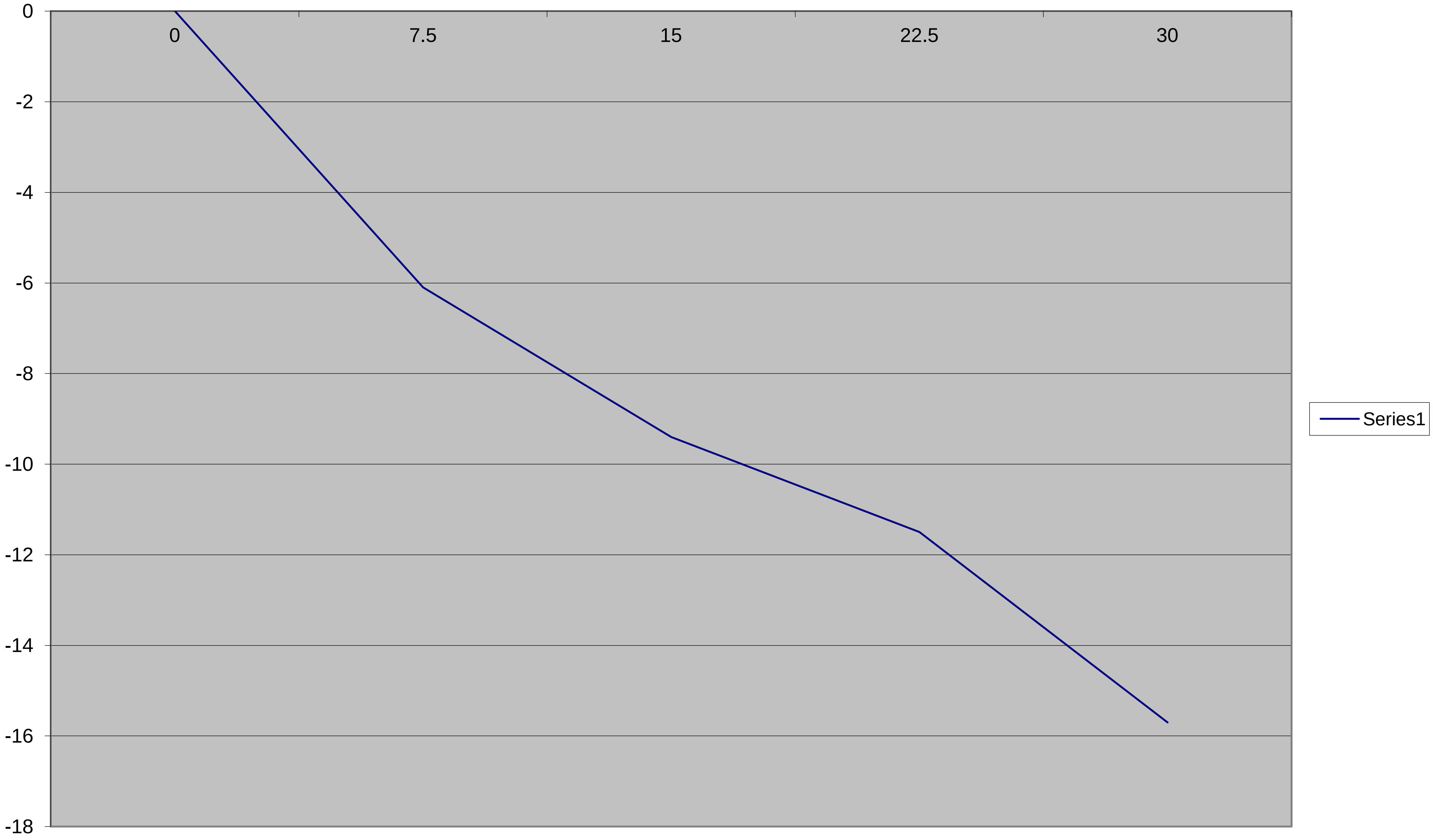
The results in Tables B.1 and B.2 were used as system checks to ensure that the ASFI system was operating correctly. This was done by measuring the advance front of each furrow and identifying problems. These tables also include suggestions to eliminate the problems.

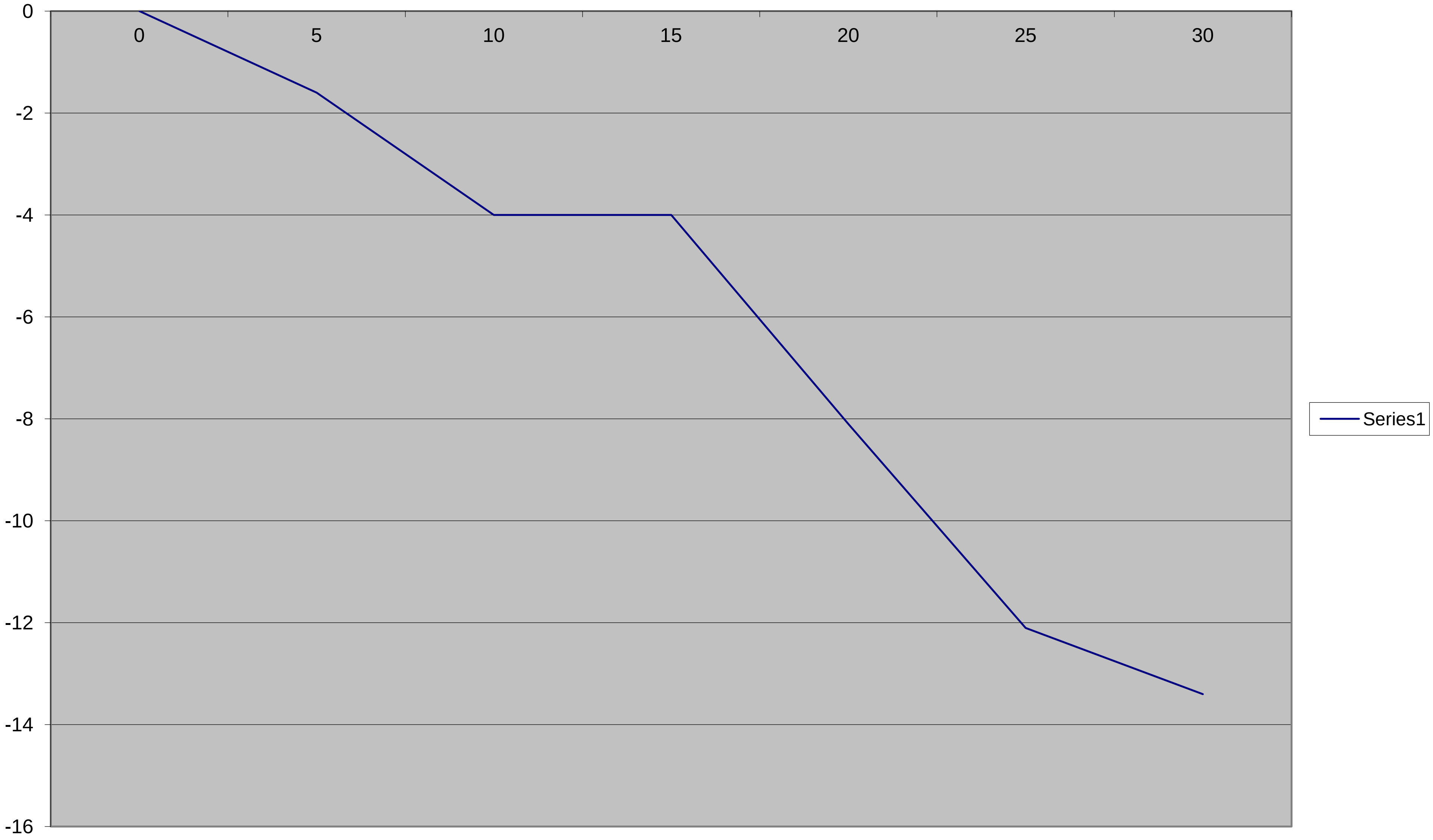
Table B.1 Advance times for ASFI Line 1

Location	**Advance time (min:sec)**	**Comments**
B1	11:05	Furrow overtopping at 30 min, need to make deeper at start
B2	14:55	
B3	26:50	slower emitter rate, check emitter for blockages
B4	19:25	fast emitter rate as a result of slow B3 emitter
B5	21:40	fast emitter rate as a result of slow B3 emitter
B6	50:00 (Estimate)	advance front was 0.5 m from end at 45 min. Remove obstructions from furrow and smooth
B7	60:00 (Estimate)	advance front was10 m from end at 45 min. Remove obstructions and smooth
	26:34	**Average Block B excluding guard line (end furrows)**
I1	27:20	
I2	33:00	
I3	26:58	
I4	22:55	
I5	29:25	
I6	27:40	
I7	17:40	
I8	16:36	
I9	16:51	
I10	26:30	
I11	43:30	
I12	27:30	
I13	30:50	
I14	17:02	
I15	22:50	
I16	22:45	
I17	60:00	advance front was10 m from end at 45 min. Remove obstructions and smooth
	25:28	**Average Block I excluding guard line (end furrows)**

Table B.2 Advance times for ASFI Line 2

Location	Advance Time (min:sec)	Comments
D1	14:02	Furrow overtopping at 25 min, need to make deeper near start
D2	17:57	
D3	19:55	
D4	25:20	
D5	30:00	
D6	17:48	
D7	19:50	Furrow overtopping at 25 min, need to make deeper near start
	22:12	**Average Block D excluding guard line (end furrows)**
G1	54:00	Advance front was7m from end at 45 min, need to smooth out furrow
G2	21:50	
G3	14:05	
G4	18:28	
G5	27:00	
G6	37:50	
G7	36:10	
G8	19:30	
G9	44:00	
G10	20:10	
G11	38:30	
G12	43:55	Very slow start due to ridge at approx. 1.5 from start
G13	49:00	Very slow start due to ridge at approx. 1.5 from start
G14	17:52	
G15	28:40	
G16	49:00	Advance front reached 3m from end dueto a mole hole
G17	55:00	Advance front was 8 m from end at 45 min, smooth out furrow
	34:31	**Average Block G excluding guard line (end furrows)**


0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
7.5
15
22.5
30
Series1


0
-2
-4
-6
-8
-10
-12
-14
-16
0
5
10
15
20
25
30
Series1

Distance (m)	Level (cm)					Distance (m)	Level (cm)	
0	99.5	0				0	91.8	0
5	97.9	-1.6				7.5	85.7	-6.1
10	95.5	-4				15	82.4	-9.4
15	95.5	-4	1:	375	0.002667	22.5	80.3	-11.5
20	91.4	-8.1				30	76.1	-15.7
25	87.4	-12.1						
30	86.1	-13.4	1:	223.8806	0.004467			

1: 159.5745 0.006267

1: 191.0828 0.005233

Distance (m)	Advance Front Time (m.s)	Recession Front Time (m.s)		Advance Front Time (s)	Recession Front Time (s)		Distance (m)
7.5	1.32	22.11		92.00	1331.00	1.53	7.5
15	3.55	23.46		235.00	1426.00	3.92	15
22.5	8.11	26.54		491.00	1614.00	8.18	22.5
30	13.35	39.11		815.00	2351.00	13.58	
Cut off	20.00	(m.s)	1200.00	(s)			Cut off
Bucket Vol (l)	Time (m.s)	Time (s)	Q (l/s)	Q (l/min)			Bucket Vol (l)
15	0.56	56.00	0.267857	16.0714286			15
15	1.37	97.00	0.154639	9.27835052			15
Volume	0.25	m3	0.211248	(Q avg)			Volume
			SIRMOD 2	point			
Length	30.00	m	a	0.6516			Length
Spacing	1.80	m	k	0.00075			Spacing
Depth	4.69	mm	fo	0.000145			Depth

Distance (m)	Advance Front Time (m.s)	Recession Front Time (m.s)		Advance Front Time (s)	Recession Front Time (s)		Distance (m)
5	0.55	12.43		55.00	763.00		5
10				0.00	0.00		10
15	2.56	16.06		176.00	966.00		15
20	3.54	16.52		234.00	1012.00		20
25	4.46	18.11		286.00	1091.00		25
30	5.56	61.00		356.00	3660.00		30
Cut off	10.00	(m.s)	600.00	(s)			Cut off
Bucket Vol (l)	Time (m.s)	Time (s)	Q (l/s)	Q (l/min)			Bucket Vol (l)
15	0.42	42.00	0.357143	21.4285714			10
15	0.43	43.00	0.348837	20.9302326			10
Volume	0.21	m3					Volume
Length	30.00	m					Length
Spacing	1.80	m					Spacing
Depth	3.92	mm					Depth

0.0012

Advance Front Time (m.s)	Recession Front Time (m.s)		Advance Front Time (s)	Recession Front Time (s)
1.04	11.06		64.00	666.00
2.17	12.51		137.00	771.00
4.00	25.17		240.00	1517.00

7.00 (m.s) 420.00 (s)

Time (m.s)	Time (s)	Q (l/s)	Q (l/min)
1.06	66.00	0.227273	13.63636
1.03	63.00	0.238095	14.28571

0.10 m3

30.00 m
1.80 m
1.81 mm

Advance Front Time (m.s)	Recession Front Time (m.s)		Advance Front Time (s)	Recession Front Time (s)	
2.07	22.20		127.00	1340.00	2.116667
4.17	23.00		257.00	1380.00	4.283333
6.17	25.00		377.00	1500.00	6.283333
7.54	25.00		474.00	1500.00	7.9
9.14	30.40		554.00	1840.00	9.233333
11.14	120.39		674.00	7239.00	11.23333

15.00 (m.s) 900.00 (s)

Time (m.s)	Time (s)	Q (l/s)	Q (l/min)
1.17	77.00	0.12987	7.792208
1.17	77.00	0.12987	7.792208

0.12 m3

30.00 m
1.80 m
2.16 mm

	l/min	l/s	Inflow time	Length	Spacing	Depth	%depth chg	Vol
100	16	0.266667	30	30	1.8	8.888889	100	0.48
110	17.6	0.293333	30	30	1.8	9.777778	110	
121	19.36	0.322667	30	30	1.8	10.75556	121	
133.1	21.296	0.354933	30	30	1.8	11.83111	133.1	
146.41	23.4256	0.390427	30	30	1.8	13.01422	146.41	
161.051	25.76816	0.429469	30	30	1.8	14.31564	161.051	

1	1000	0.001
1	500	0.002
1	200	0.005
1	100	0.01
1	1000	0.001

11.43053
2.541644
1.652756
0.674978
0.400578
1.583689
2.885111

0.851995

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Height Difference (m)	Lateral Slope 1:
		Lateral Slope 1 :		10				
End Emitter	11.251							
1	11.251	0.000188	1.8	0.02	0.597	0.042	0.090	20.000
2	22.502	0.000375	1.8	0.02	1.194	0.153	0.090	20.000
3	33.753	0.000563	1.8	0.02	1.791	0.323	0.090	20.000
4	45.004	0.00075	1.8	0.032	0.933	0.056	0.090	20.000
5	56.255	0.000938	1.8	0.032	1.166	0.084	0.090	20.000
6	67.506	0.001125	1.8	0.032	1.399	0.118	0.090	20.000
7	78.757	0.001313	1.8	0.032	1.632	0.157	0.090	20.000
8	90.008	0.0015	1.8	0.04	1.194	0.068	0.090	20.000
9	90	0.001688	1.8	0.04	1.343	0.085	0.090	20.000
10	112.51	0.001875	1.8	0.04	1.492	0.103	0.090	20.000
11	123.761	0.002063	1.8	0.04	1.641	0.123	0.090	20.000
12	135.012	0.00225	1.8	0.04	1.791	0.144	0.090	20.000
13	146.263	0.002438	1.8	0.04	1.940	0.167	0.090	20.000
14	157.514	0.002625	1.8	0.05	1.337	0.065	0.090	20.000
15	168.765	0.002813	1.8	0.05	1.433	0.073	0.090	20.000
16	180.016	0.003	1.8	0.05	1.528	0.083	0.090	20.000
17	191.267	0.003188	1.8	0.05	1.624	0.093	0.090	20.000

Pressure at Emitter (kPa)	Pressure at Emitter (m)	Pressure in Lateral P1 (Pa)	Required Discharge ((m3/s)	Diameter of emmitter pipe (m)	Length Emmitter pipe (cm)	Diameter o lateral d1 m
49.730	4.973	49730.00	0.000188	0.01	55.89	0.02
49.253	4.925	49252.80	0.000188	0.01	55.32	0.02
49.879	4.988	49879.09	0.000188	0.01	56.07	0.02
52.213	5.221	52213.24	0.000188	0.01	58.84	0.02
51.872	5.187	51871.62	0.000188	0.01	58.25	0.032
51.816	5.182	51815.74	0.000188	0.01	58.19	0.032
52.099	5.210	52098.91	0.000188	0.01	58.52	0.032
52.773	5.277	52773.02	0.000188	0.01	59.32	0.032
52.553	5.255	52552.86	0.000188	0.01	59.04	0.04
52.498	5.250	52498.42	0.000188	0.01	58.98	0.04
52.626	5.263	52626.17	0.000188	0.01	59.13	0.04
52.952	5.295	52952.32	0.000188	0.01	59.52	0.04
53.493	5.349	53492.88	0.000188	0.01	60.16	0.04
54.264	5.426	54263.62	0.000188	0.01	61.07	0.04
54.010	5.401	54010.00	0.000188	0.01	60.76	0.05
53.844	5.384	53844.49	0.000188	0.01	60.57	0.05
53.772	5.377	53772.22	0.000188	0.01	60.48	0.05
53.798	5.380	53798.31	0.000188	0.01	60.51	0.05

Area emmi pipe A2 m2	Area lateral A1 m2	Velocity in emiter pipe V2 m/s	Velocity in lateral V1 m/s	Reynolds N emiter pipe	f factor	P1/pg	v12/2g
7.85E-05	0.000314	2.387536353	0.596884	23867.25	0.295424	5.069317023	0.018159
7.85E-05	0.000314	2.387536353	0.596884	23867.25	0.295424	5.020672428	0.018159
7.85E-05	0.000314	2.387536353	0.596884	23867.25	0.295424	5.084515103	0.018159
7.85E-05	0.000314	2.387536353	0.596884	23867.25	0.295424	5.322450733	0.018159
7.85E-05	0.000804	2.387536353	0.233158	23867.25	0.295424	5.287626717	0.002771
7.85E-05	0.000804	2.387536353	0.233158	23867.25	0.295424	5.28193053	0.002771
7.85E-05	0.000804	2.387536353	0.233158	23867.25	0.295424	5.310796228	0.002771
7.85E-05	0.000804	2.387536353	0.233158	23867.25	0.295424	5.379512268	0.002771
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.357070258	0.001135
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.351520667	0.001135
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.364542864	0.001135
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.39779018	0.001135
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.452892748	0.001135
7.85E-05	0.001257	2.387536353	0.149221	23867.25	0.295424	5.531459812	0.001135
7.85E-05	0.001963	2.387536353	0.095501	23867.25	0.295424	5.505606955	0.000465
7.85E-05	0.001963	2.387536353	0.095501	23867.25	0.295424	5.488734748	0.000465
7.85E-05	0.001963	2.387536353	0.095501	23867.25	0.295424	5.481368287	0.000465
7.85E-05	0.001963	2.387536353	0.095501	23867.25	0.295424	5.484027672	0.000465

z1	E1	P2/pg	v22/2g	z1	E2	flv22/2gd	l
						xl	m
0	5.087476	0	0.290537	0	0.290537	8.583139	0.558879
0	5.038831	0	0.290537	0	0.290537	8.583139	0.553212
0	5.102674	0	0.290537	0	0.290537	8.583139	0.56065
0	5.340609	0	0.290537	0	0.290537	8.583139	0.588371
0	5.290397	0	0.290537	0	0.290537	8.583139	0.582521
0	5.284701	0	0.290537	0	0.290537	8.583139	0.581858
0	5.313567	0	0.290537	0	0.290537	8.583139	0.585221
0	5.382283	0	0.290537	0	0.290537	8.583139	0.593227
0	5.358205	0	0.290537	0	0.290537	8.583139	0.590421
0	5.352656	0	0.290537	0	0.290537	8.583139	0.589775
0	5.365678	0	0.290537	0	0.290537	8.583139	0.591292
0	5.398925	0	0.290537	0	0.290537	8.583139	0.595166
0	5.454028	0	0.290537	0	0.290537	8.583139	0.601585
0	5.532595	0	0.290537	0	0.290537	8.583139	0.610739
0	5.506072	0	0.290537	0	0.290537	8.583139	0.607649
0	5.4892	0	0.290537	0	0.290537	8.583139	0.605683
0	5.481833	0	0.290537	0	0.290537	8.583139	0.604825
0	5.484493	0	0.290537	0	0.290537	8.583139	0.605135

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Height Difference (m)	Lateral Slope 1:
		Lateral Slope 1 :		10				
End Emitter	11.25							
1	11.25	0.000188	1.8	0.02	0.597	0.042	0.093	19.417
2	22.5	0.000375	1.8	0.02	1.194	0.153	0.093	19.417
3	33.75	0.000563	1.8	0.02	1.790	0.323	0.093	19.417
4	45	0.00075	1.8	0.032	0.933	0.056	0.093	19.417
5	56.25	0.000938	1.8	0.032	1.166	0.084	0.093	19.417
6	67.5	0.001125	1.8	0.032	1.399	0.118	0.093	19.417
7	78.75	0.001313	1.8	0.032	1.632	0.157	0.093	19.417
8	90	0.0015	1.8	0.04	1.194	0.068	0.093	19.417
9	101.25	0.001688	1.8	0.04	1.343	0.085	0.093	19.417
10	112.5	0.001875	1.8	0.04	1.492	0.103	0.093	19.417
11	123.75	0.002063	1.8	0.04	1.641	0.123	0.093	19.417
12	135	0.00225	1.8	0.04	1.790	0.144	0.093	19.417
13	146.25	0.002438	1.8	0.04	1.940	0.167	0.093	19.417
14	157.5	0.002625	1.8	0.05	1.337	0.065	0.093	19.417
15	168.75	0.002813	1.8	0.05	1.432	0.073	0.093	19.417
16	180	0.003	1.8	0.05	1.528	0.083	0.093	19.417
17	191.25	0.003188	1.8	0.05	1.623	0.093	0.093	19.417
18	202.5	0.003375	5.8	0.05	1.719	0.332	5.104	10.000
19	213.75	0.003563	1.8	0.05	1.814	0.114	0.088	20.455
20	225	0.00375	1.8	0.05	1.910	0.125	0.088	20.455
21	236.25	0.003938	1.8	0.05	2.005	0.137	0.088	20.455
22	247.5	0.004125	1.8	0.05	2.101	0.149	0.088	20.455
23	258.75	0.004313	1.8	0.05	2.196	0.162	0.088	20.455
24	270	0.0045	1.8	0.05	2.292	0.175	0.088	20.455

16.2 m^3/hr

Pressure at Emitter (kPa)	Pressure at Emitter (m)
51.200	5.120
50.696	5.070
51.295	5.129
53.601	5.360
53.233	5.323
53.150	5.315
53.406	5.341
54.052	5.405
53.805	5.381
53.724	5.372
53.824	5.382
54.123	5.412
54.636	5.464
55.380	5.538
55.099	5.510
54.907	5.491
54.807	5.481
54.806	5.481
52.323	5.232
52.581	5.258
52.952	5.295
53.441	5.344
54.054	5.405
54.795	5.479
55.668	5.567

Pressure in Lateral P1 (Pa)	Required Discharge Q2 (m3/s)	Diameter o emmitter p (m)	Length Emmitter pipe (cm)
51200.00	0.0001875	0.005	2.97
50695.73	0.0001875	0.008	210.02
51294.77	0.0001875	0.008	212.89
53601.39	0.0001875	0.01	60.50
53232.67	0.0001875	0.01	59.88
53149.65	0.0001875	0.01	59.78
53405.63	0.0001875	0.01	60.09
54052.48	0.0001875	0.01	60.85
53805.21	0.0001875	0.01	60.54
53723.63	0.0001875	0.01	60.44
53824.21	0.0001875	0.01	60.56
54123.16	0.0001875	0.01	60.92
54636.48	0.0001875	0.01	61.53
55379.95	0.0001875	0.01	62.41
55099.23	0.0001875	0.01	62.07
54906.59	0.0001875	0.01	61.84
54807.19	0.0001875	0.01	61.72
54806.12	0.0001875	0.01	61.72
52322.85	0.0001875	0.01	58.77
52580.59	0.0001875	0.01	59.08
52951.70	0.0001875	0.01	59.52
53441.13	0.0001875	0.01	60.10
54053.78	0.0001875	0.01	60.83
54794.50	0.0001875	0.01	61.71
55668.14	0.0001875	0.01	62.75

Diameter o lateral d1 m	Area emmitter pipe A2 m2	Area lateral A1 m2	Velocity in emiter pip m/s	Velocity in lateral V1 m/s	Reynolds No. emiter pipe	f factor	P1/pg
0.02	1.9635E-05	0.000314	9.549297	0.596831	47730.25464	0.021379	5.219164
0.02	5.02655E-05	0.000314	3.730194	0.596831	29831.40915	0.024045	5.16776
0.02	5.02655E-05	0.000314	3.730194	0.596831	29831.40915	0.024045	5.228825
0.02	7.85398E-05	0.000314	2.387324	0.596831	23865.12732	0.295424	5.463954
0.032	7.85398E-05	0.000804	2.387324	0.233137	23865.12732	0.295424	5.426368
0.032	7.85398E-05	0.000804	2.387324	0.233137	23865.12732	0.295424	5.417906
0.032	7.85398E-05	0.000804	2.387324	0.233137	23865.12732	0.295424	5.443999
0.032	7.85398E-05	0.000804	2.387324	0.233137	23865.12732	0.295424	5.509937
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.484731
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.476415
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.486667
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.517142
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.569468
0.04	7.85398E-05	0.001257	2.387324	0.149208	23865.12732	0.295424	5.645255
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.616639
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.597002
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.586869
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.586761
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.333624
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.359897
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.397727
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.447618
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.510069
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.585576
0.05	7.85398E-05	0.001963	2.387324	0.095493	23865.12732	0.295424	5.674632

v12/2g	z1	E1	P2/pg	v22/2g	z1	E2	flv22/2gd xl	l m
0.018155	0	5.237319	0	4.647761	0	4.647761	19.87295	0.029666
0.018155	0	5.185915	0	0.709192	0	0.709192	2.131535	2.100234
0.018155	0	5.24698	0	0.709192	0	0.709192	2.131535	2.128883
0.018155	0	5.482109	0	0.290485	0	0.290485	8.581629	0.60497
0.00277	0	5.429139	0	0.290485	0	0.290485	8.581629	0.598797
0.00277	0	5.420676	0	0.290485	0	0.290485	8.581629	0.597811
0.00277	0	5.446769	0	0.290485	0	0.290485	8.581629	0.600851
0.00277	0	5.512707	0	0.290485	0	0.290485	8.581629	0.608535
0.001135	0	5.485866	0	0.290485	0	0.290485	8.581629	0.605407
0.001135	0	5.477549	0	0.290485	0	0.290485	8.581629	0.604438
0.001135	0	5.487802	0	0.290485	0	0.290485	8.581629	0.605633
0.001135	0	5.518277	0	0.290485	0	0.290485	8.581629	0.609184
0.001135	0	5.570603	0	0.290485	0	0.290485	8.581629	0.615281
0.001135	0	5.646389	0	0.290485	0	0.290485	8.581629	0.624113
0.000465	0	5.617103	0	0.290485	0	0.290485	8.581629	0.6207
0.000465	0	5.597467	0	0.290485	0	0.290485	8.581629	0.618412
0.000465	0	5.587334	0	0.290485	0	0.290485	8.581629	0.617231
0.000465	0	5.587226	0	0.290485	0	0.290485	8.581629	0.617219
0.000465	0	5.334089	0	0.290485	0	0.290485	8.581629	0.587721
0.000465	0	5.360361	0	0.290485	0	0.290485	8.581629	0.590783
0.000465	0	5.398192	0	0.290485	0	0.290485	8.581629	0.595191
0.000465	0	5.448083	0	0.290485	0	0.290485	8.581629	0.601004
0.000465	0	5.510534	0	0.290485	0	0.290485	8.581629	0.608282
0.000465	0	5.586041	0	0.290485	0	0.290485	8.581629	0.61708
0.000465	0	5.675097	0	0.290485	0	0.290485	8.581629	0.627458

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Height Difference (m)	Lateral Slope 1:
		Lateral Slope 1 :						
End Emitter	11.25							
1	11.25	0.000188	1.8	0.02	0.597	0.042	0.085	21.176
2	22.5	0.000375	1.8	0.02	1.194	0.153	0.085	21.176
3	33.75	0.000563	1.8	0.02	1.790	0.323	0.085	21.176
4	45	0.00075	1.8	0.032	0.933	0.056	0.085	21.176
5	56.25	0.000938	1.8	0.032	1.166	0.084	0.085	21.176
6	67.5	0.001125	1.8	0.032	1.399	0.118	0.085	21.176
7	78.75	0.001313	1.8	0.032	1.632	0.157	0.085	21.176
8	90	0.0015	1.8	0.04	1.194	0.068	0.085	21.176
9	101.25	0.001688	1.8	0.04	1.343	0.085	0.085	21.176
10	112.5	0.001875	1.8	0.04	1.492	0.103	0.085	21.176
11	123.75	0.002063	1.8	0.04	1.641	0.123	0.085	21.176
12	135	0.00225	1.8	0.04	1.790	0.144	0.085	21.176
13	146.25	0.002438	1.8	0.04	1.940	0.167	0.085	21.176
14	157.5	0.002625	1.8	0.05	1.337	0.065	0.085	21.176
15	168.75	0.002813	1.8	0.05	1.432	0.073	0.085	21.176
16	180	0.003	1.8	0.05	1.528	0.083	0.085	21.176
17	191.25	0.003188	1.8	0.05	1.623	0.093	0.085	21.176
18	202.5	0.003375	5.8	0.05	1.719	0.332	0.110	10.000
19	213.75	0.003563	1.8	0.05	1.814	0.114	0.100	18.000
20	225	0.00375	1.8	0.05	1.910	0.125	0.100	18.000
21	236.25	0.003938	1.8	0.05	2.005	0.137	0.100	18.000
22	247.5	0.004125	1.8	0.05	2.101	0.149	0.100	18.000
23	258.75	0.004313	1.8	0.05	2.196	0.162	0.100	18.000
24	270	0.0045	1.8	0.05	2.292	0.175	0.100	18.000

16.2 m^3/h

Pressure at Emitter (kPa)	Pressure at Emitter (m)	Pressure in Lateral P1 (Pa)	Required Discharge ((m3/s)	Diameter of emmitter pipe (m)	Length Emmitter pipe (cm)	Diameter o lateral d1 m
49.170	4.917	49170.00	0.000188	0.01	55.23	0.02
48.743	4.874	48742.73	0.000188	0.01	54.73	0.02
49.419	4.942	49418.77	0.000188	0.01	55.53	0.02
51.802	5.180	51802.39	0.000188	0.01	58.36	0.02
51.511	5.151	51510.67	0.000188	0.01	57.83	0.032
51.505	5.150	51504.65	0.000188	0.01	57.83	0.032
51.838	5.184	51837.63	0.000188	0.01	58.22	0.032
52.561	5.256	52561.48	0.000188	0.01	59.08	0.032
52.391	5.239	52391.21	0.000188	0.01	58.86	0.04
52.387	5.239	52386.63	0.000188	0.01	58.86	0.04
52.564	5.256	52564.21	0.000188	0.01	59.07	0.04
52.940	5.294	52940.16	0.000188	0.01	59.51	0.04
53.530	5.353	53530.48	0.000188	0.01	60.21	0.04
54.351	5.435	54350.95	0.000188	0.01	61.19	0.04
54.147	5.415	54147.23	0.000188	0.01	60.94	0.05
54.032	5.403	54031.59	0.000188	0.01	60.80	0.05
54.009	5.401	54009.19	0.000188	0.01	60.78	0.05
54.085	5.409	54085.12	0.000188	0.01	60.87	0.05
51.602	5.160	51601.85	0.000188	0.01	57.92	0.05
51.740	5.174	51739.59	0.000188	0.01	58.08	0.05
51.991	5.199	51990.70	0.000188	0.01	58.38	0.05
52.360	5.236	52360.13	0.000188	0.01	58.82	0.05
52.853	5.285	52852.78	0.000188	0.01	59.40	0.05
53.474	5.347	53473.50	0.000188	0.01	60.14	0.05
54.227	5.423	54227.14	0.000188	0.01	61.03	0.05

Area emmi pipe A2 m2	Area lateral A1 m2	Velocity in emiter pipe V2 m/s	Velocity in lateral V1 m/s	Reynolds N emiter pipe	f factor	P1/pg	v12/2g
7.85E-05	0.000314	2.387324146	0.596831	23865.13	0.295424	5.012232416	0.018155
7.85E-05	0.000314	2.387324146	0.596831	23865.13	0.295424	4.968677566	0.018155
7.85E-05	0.000314	2.387324146	0.596831	23865.13	0.295424	5.037591472	0.018155
7.85E-05	0.000314	2.387324146	0.596831	23865.13	0.295424	5.280569676	0.018155
7.85E-05	0.000804	2.387324146	0.233137	23865.13	0.295424	5.250833131	0.00277
7.85E-05	0.000804	2.387324146	0.233137	23865.13	0.295424	5.25021962	0.00277
7.85E-05	0.000804	2.387324146	0.233137	23865.13	0.295424	5.284162306	0.00277
7.85E-05	0.000804	2.387324146	0.233137	23865.13	0.295424	5.357948775	0.00277
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.340592197	0.001135
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.340125258	0.001135
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.358227051	0.001135
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.396550633	0.001135
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.45672587	0.001135
7.85E-05	0.001257	2.387324146	0.149208	23865.13	0.295424	5.540361741	0.001135
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.519594878	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.507807188	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.505523678	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.513264365	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.260127519	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.274167832	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.299765677	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.337424165	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.387642786	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.450917601	0.000465
7.85E-05	0.001963	2.387324146	0.095493	23865.13	0.295424	5.527741417	0.000465

z1	E1	P2/pg	v22/2g	z1	E2	flv22/2gd xl	l m
0	5.030388	0	0.290485	0	0.290485	8.581629	0.552331
0	4.986833	0	0.290485	0	0.290485	8.581629	0.547256
0	5.055747	0	0.290485	0	0.290485	8.581629	0.555286
0	5.298725	0	0.290485	0	0.290485	8.581629	0.5836
0	5.253603	0	0.290485	0	0.290485	8.581629	0.578342
0	5.25299	0	0.290485	0	0.290485	8.581629	0.578271
0	5.286933	0	0.290485	0	0.290485	8.581629	0.582226
0	5.360719	0	0.290485	0	0.290485	8.581629	0.590824
0	5.341727	0	0.290485	0	0.290485	8.581629	0.588611
0	5.34126	0	0.290485	0	0.290485	8.581629	0.588557
0	5.359362	0	0.290485	0	0.290485	8.581629	0.590666
0	5.397685	0	0.290485	0	0.290485	8.581629	0.595132
0	5.457861	0	0.290485	0	0.290485	8.581629	0.602144
0	5.541496	0	0.290485	0	0.290485	8.581629	0.61189
0	5.52006	0	0.290485	0	0.290485	8.581629	0.609392
0	5.508272	0	0.290485	0	0.290485	8.581629	0.608018
0	5.505988	0	0.290485	0	0.290485	8.581629	0.607752
0	5.513729	0	0.290485	0	0.290485	8.581629	0.608654
0	5.260592	0	0.290485	0	0.290485	8.581629	0.579157
0	5.274633	0	0.290485	0	0.290485	8.581629	0.580793
0	5.30023	0	0.290485	0	0.290485	8.581629	0.583776
0	5.337889	0	0.290485	0	0.290485	8.581629	0.588164
0	5.388108	0	0.290485	0	0.290485	8.581629	0.594016
0	5.451382	0	0.290485	0	0.290485	8.581629	0.601389
0	5.528206	0	0.290485	0	0.290485	8.581629	0.610341

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Calculation of length of pipe to give a certain flow out of a microflood emitter

Kinematic viscosity@20C	1.00034	mm2/s	
Gravity	9.81	m/s2	
Density	1000	kg/m3	
Diameter of polypipe d2	0.01	m	
Diameter of lateral d1	0.07	m	
Required Discharge Q2	0.000166667	m3/s	
Pressure in Lateral P1	45000	Pa	
Area polypipe A2	7.85398E-05	m2	
Area lateral A1	0.003848451	m2	
Velocity in polypipe V2	2.122065908	m/s	
Velocity in lateral V1	0.043307468	m/s	
Reynolds No. polypipe	21213.44651		
f factor	0.026183896		
P1/pg	4.587155963		
v12/2g	9.55931E-05		0.000955931
z1	0	4.587252	
P2/pg	0		
v22/2g	0.229519048		
z1	0	0.229519	
flv22/2gd	0.600970297	xl	0.330533664
l	7.25116121	m	
	725.116121	cm	

Friction loss in pipe

Kinematic viscosity@20C	1.00034	mm2/s
Gravity	9.81	m/s2
Density	1000	kg/m3
Diameter of pipe	0.05	m
Length of pipe	9.45	m
Required Discharge Q2	0.000166667	m3/s
Area pipe	0.001963495	m2
Velocity in pipe	0.084882636	m/s
Reynolds No. polypipe	4242.689301	
f factor	0.039154058	
flv2/2gd (Darcy Weibach)	0.002717548	m
v2/2g	0.00036723	m
Total Head	0.003084779	
hf (Hazen Williams)	0.002056906	m

Total Area of Irrigation Block	1	ha		
Design peak crop evapotranspiration rate	6	mm/d		
Assumed efficiency	100	%		
Irrigation operating hours per day	24	hr		
Required flowrate to supply water to block	0.000694	m3/s		
	0.694444	l/s/ha		
Actual flow available to block	0.0146	m3/s		
Flow rate into individual micro-furrows	16	l/min		
Theoretical No. of concurrent furrows	54.8			
Furrow Length	25	m		
Furrow Spacing	1.8	m		
Theoretical area per tilt valve	0.246375	ha		
Theoretical No. tilt valves per ha	4.06			
Design Application Depth (if spread over total area)	15	mm		
Tilt valve 'ON' time	42.1875	minutes		
Time to irrigate 1 ha	171.2329	minutes		
	2.85	hrs		
Time to irrigate	10	ha		
	28.53881	hrs		
	2.378234	days @	12	hrs/day
Effective mm/d equivalent	6.3072	mm/d		

Total Area of Irrigation Block	21	ha
Design peak crop evapotranspiration rate	6	mm/d
Assumed efficiency	100	%
Irrigation operating hours per day	24	hr
Required flowrate to supply water to block	0.014583	m3/s
	0.694444	l/s/ha
Actual flow available to block	0.014583	m3/s
Flow rate into individual micro-furrows	16	l/min
Theoretical No. of concurrent furrows	54.7	
Furrow Length	25	m
Furrow Spacing	1.8	m
Theoretical area per tilt valve	0.246094	ha
Theoretical No. tilt valves per ha	4.06	
Design Application Depth	15	mm
Tilt valve 'ON' time	42.1875	minutes
Time to irrigate 1 ha	171.4286	minutes
	2.86	hrs

For Drip Irrigation Laterals

For laminar flow $Re < 2000$ $f = 64/Re$

For turbulent flow $2000 < Re < 10^5$ $f = 0.316/ Re^{0.25}$

Fully turbulent flow $10^5 < Re \leq 10^7$ $f = 0.130/Re^{0.172}$ or $f = 0.0056 + 0.5/Re^{0.32}$ (Fanni

cited by Yang, Y. and Nishiyama, S. 1995. Trans ASAE 38(5) - In ASAE's 'Irrig Engineering' collation of

se also Ag Eng in SA 1989.

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ing equation)

Trans ASAE irrig papers

		Jan	Feb	Mar	Apr	May	Jun
Rainfall	mm	141	117	113	48	24	13
Ave. daily ET	mm	4.6	4.4	3.8	3.1	2.6	2.3
days		31	28	31	30	31	30
A-pan	mm	142.6	123.2	117.8	93	80.6	69
Crop factor	-	0.8	0.8	0.8	0.8	0.8	0.8
Allow depletion	-	0.5	0.5	0.5	0.5	0.5	0.5
NRD	mm	1200	1200	1200	1200	1200	1200
NSD	mm	1000	1000	1000	1000	1000	1000
ERD	mm	1000	1000	1000	1000	1000	1000
Eff rainfall	mm	60.5	48.5	46.5	14	2	0
ET	mm	114.08	98.56	94.24	74.4	64.48	55.2
NIRm	mm/month	53.58	50.06	47.74	60.4	62.48	55.2
NIRd	mm/day	1.728	1.788	1.540	2.013	2.015	1.840
FC	m/m	0.258	0.258	0.258	0.258	0.258	0.258
WP	m/m	0.132	0.132	0.132	0.132	0.132	0.132
WHC	mm	125.8	125.8	125.8	125.8	125.8	125.8
AW	mm	125.8	125.8	125.8	125.8	125.8	125.8
RAW	mm	62.9	62.9	62.9	62.9	62.9	62.9
Wetted area	%	36	36	36	36	36	36
System Efficiency	%	95	95	95	95	95	95
Tc	days	13.1	12.7	14.7	11.2	11.2	12.3
GIRc	mm/cycle	23.8	23.8	23.8	23.8	23.8	23.8
Tc Prac	days	5	5	5	5	5	5
GIRc Prac	mm/cycle	9.1	9.4	8.1	10.6	10.6	9.7
Ld	m	1.8	1.8	1.8	1.8	1.8	1.8
Le	m	0.5	0.5	0.5	0.5	0.5	0.5
Ts	h	6	6	6	6	6	6
qe	l/h	1.36	1.41	1.22	1.59	1.59	1.45
qe catalogue	l/h	2.3	2.3	2.3	2.3	2.3	2.3
Ts calculated	h	3.6	3.7	3.2	4.1	4.2	3.8
Field area	ha	0.5	0.5	0.5	0.5	0.5	0.5
Sets/day	-	1	1	1	1	1	1
T	h/cycle	3.6	3.7	3.2	4.1	4.2	3.8
System Q	m^3/h	12.77778	12.77778	12.77778	12.77778	12.77778	12.77778
n emitter	-	5556	5556	5556	5556	5556	5556
Area group	ha	0.5	0.5	0.5	0.5	0.5	0.5
Block area	ha	0.111	0.111	0.111	0.111	0.111	0.111
Lateral length	m	30	30	30	30	30	30
Lateral spacing	m	1.8	1.8	1.8	1.8	1.8	1.8
Block length	m	30	30	30	30	30	30

Block width	m	37	37	37	37	37	37
# laterals		20.6	20.6	20.6	20.6	20.6	20.6
# laterals act		21	21	21	21	21	21
Prac Qs	m^3/h	2.98494	2.98494	2.98494	2.98494	2.98494	2.98494

Jul	Aug	Sep	Oct	Nov	Dec	MAP
11	31	60	74	104	108	844
2.5	3	3.6	3.9	4.4	4.6	
31	31	30	31	30	31	
77.5	93	108	120.9	132	142.6	
0.8	0.8	0.8	0.8	0.8	0.8	
0.5	0.5	0.5	0.5	0.5	0.5	
1200	1200	1200	1200	1200	1200	
1000	1000	1000	1000	1000	1000	
1000	1000	1000	1000	1000	1000	
0	5.5	20	27	42	44	
62	74.4	86.4	96.72	105.6	114.08	
62	68.9	66.4	69.72	63.6	70.08	
2.000	2.223	2.213	2.249	2.120	2.261	
0.258	0.258	0.258	0.258	0.258	0.258	
0.132	0.132	0.132	0.132	0.132	0.132	
125.8	125.8	125.8	125.8	125.8	125.8	
125.8	125.8	125.8	125.8	125.8	125.8	
62.9	62.9	62.9	62.9	62.9	62.9	
36	36	36	36	36	36	
95	95	95	95	95	95	
11.3	10.2	10.2	10.1	10.7	10.0	
23.8	23.8	23.8	23.8	23.8	23.8	
5	5	5	5	5	5	
10.5	11.7	11.6	11.8	11.2	11.9	
1.8	1.8	1.8	1.8	1.8	1.8	
0.5	0.5	0.5	0.5	0.5	0.5	
6	6	6	6	6	6	
1.58	1.75	1.75	1.78	1.67	1.78	
2.3	2.3	2.3	2.3	2.3	2.3	
4.1	4.6	4.6	4.6	4.4	4.7	
0.5	0.5	0.5	0.5	0.5	0.5	
1	1	1	1	1	1	
4.1	4.6	4.6	4.6	4.4	4.7	
12.77778	12.77778	12.77778	12.77778	12.77778	12.77778	
5556	5556	5556	5556	5556	5556	
0.5	0.5	0.5	0.5	0.5	0.5	
0.111	0.111	0.111	0.111	0.111	0.111	
30	30	30	30	30	30	
1.8	1.8	1.8	1.8	1.8	1.8	
30	30	30	30	30	30	

37	37	37	37	37	37
20.6	20.6	20.6	20.6	20.6	20.6
21	21	21	21	21	21
2.98494	2.98494	2.98494	2.98494	2.98494	2.98494

Description	Points	Flow Rate in sub main pipe		General Exponential					Calculated Internal Diameter of Manifold		Selected Manifold Diameter	
Symbol		**Q**		**l**	**b**	**p**	**r**	**assume hf**	**di**	**di**	**do**	**di**
Units		**l/hr**	**m^3/s**						**m**	**mm**	**mm**	**mm**
end of last lateral in 1a	1	2	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0145	14.5	14.5	14.5
Class 6 20mm	2	120	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0136	13.6466	20	20
	3	240	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0176	17.6493	20	20
	4	360	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0205	20.5149	20	20
	5	480	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0228	22.8260	20	20
	6	600	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0248	24.7965	20	20
	7	720	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0265	26.5321	20	20
	8	840	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0281	28.0940	20	20
	9	960	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0295	29.5212	20	20
	10	1080	0.0003	2.1	0.00089	1.77	4.77	0.015	0.0319	31.8529	20	20

Area of pipe	Velocity	Velocity Head	Velocity Head Loss	Gravitational head	Gravitational Head loss	Calculated Head Loss - manifold	Pressure	Head Loss - lateral	Check End Pressure in lateral
A	v	v^2/2g	(vj^2/2g)-(vi^2/2g)	h	hj-hi	hf	P	hf	Pe
m^2	m/s	m	m	m	m	m	m	m	m
0.0002	0	0	0	4.12	0	0	5.0	0	5
0.0003	0.1061	0.0006	0.0006	3.9100	-0.2100	0.0024	10.3710	0	10.37
0.0003	0.2122	0.0023	0.0017	3.9900	0.0800	0.0083	10.5829	0	10.58
0.0003	0.3183	0.0052	0.0029	4.0700	0.0800	0.0169	10.5094	0	10.51
0.0003	0.4244	0.0092	0.0040	4.1500	0.0800	0.0282	10.4435	0	10.44
0.0003	0.5305	0.0143	0.0052	4.2300	0.0800	0.0418	10.3877	0	10.39
0.0003	0.6366	0.0207	0.0063	4.3100	0.0800	0.0578	10.3443	0	10.34
0.0003	0.7427	0.0281	0.0075	4.3900	0.0800	0.0759	10.3158	0	10.32
0.0003	0.8488	0.0367	0.0086	4.4700	0.0800	0.0961	10.3042	0	10.30
0.0003	0.9549	0.0465	0.0098	4.5500	0.0800	0.1381	10.3117	0	10.31
							10.36		

Description Manc1-h9	**Points**	**Flow Rate in sub main pipe**		**General Exponential**					**Calculated Internal Diameter of Manifold**		**Selected Manifold Diameter**	
Symbol		**Q**		**l**	**b**	**p**	**r**	**assume hf**	**di**	**di**	**do**	**di**
Units		**l/hr**	**m^3/s**						**m**	**mm**	**mm**	**mm**
end of last lateral in 1a	1	2	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0145	14.5	14.5	14.5
Class 6 20mm	2	120	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0136	13.6466	20	20
	3	240	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0176	17.6493	20	20
	4	360	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0205	20.5149	20	20
	5	480	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0228	22.8260	20	20
	6	600	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0248	24.7965	20	20
	7	720	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0265	26.5321	20	20
	8	840	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0281	28.0940	20	20
	9	960	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0295	29.5212	20	20
	10	1080	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0308	30.8400	20	20
	11	1200	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0321	32.0696	20	20
	12	1320	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0332	33.2241	20	20
	13	1440	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0343	34.3143	20	20
Class 6 25mm	14	1560	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0353	35.3488	25	25
	15	1680	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0363	36.3343	25	25
	16	1800	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0373	37.2765	25	25
	17	1920	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0382	38.1800	25	25
	18	2040	0.0006	1.8	0.00089	1.77	4.77	0.015	0.0390	39.0487	25	25
	19	2160	0.0006	5.8	0.00089	1.77	4.77	0.015	0.0510	50.9740	25	25
	20	2280	0.0006	1.8	0.00089	1.77	4.77	0.015	0.0407	40.6940	25	25
Class 6 32mm	21	2400	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0415	41.4760	32	32
	22	2520	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0422	42.2337	32	32
	23	2640	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0430	42.9691	32	32
	24	2760	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0437	43.6837	32	32
Class 6 40mm	25	2880	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0444	44.3791	40	40
	26	3000	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0451	45.0564	40	40
	27	3120	0.0009	1.8	0.00089	1.77	4.77	0.015	0.0457	45.7170	40	40
	28	3240	0.0009	2.1	0.00089	1.77	4.77	0.015	0.0479	47.8844	40	40

Area of pipe	Velocity	Velocity Head	Velocity Head Loss	Gravitational head	Gravitational Head loss	Calculated Head Loss - manifold	Pressure	Head Loss - lateral	Check End Pressure in lateral
A	v	v^2/2g	(vj^2/2g)-(vi^2/2g)	h	hj-hi	hf	P	hf	Pe
m^2	m/s	m	m	m	m	m	m	m	m
0.0002	0	0	0	1.52	0	0	5.0	0	5
0.0003	0.1061	0.0006	0.0006	2.1000	0.5800	0.0024	10.8624	0	10.86
0.0003	0.2122	0.0023	0.0017	2.2050	0.1050	0.0083	10.2843	0	10.28
0.0003	0.3183	0.0052	0.0029	2.3100	0.1050	0.0169	10.1858	0	10.19
0.0003	0.4244	0.0092	0.0040	2.4150	0.1050	0.0282	10.0949	0	10.09
0.0003	0.5305	0.0143	0.0052	2.5200	0.1050	0.0418	10.0141	0	10.01
0.0003	0.6366	0.0207	0.0063	2.6250	0.1050	0.0578	9.9457	0	9.95
0.0003	0.7427	0.0281	0.0075	2.7300	0.1050	0.0759	9.8922	0	9.89
0.0003	0.8488	0.0367	0.0086	2.8350	0.1050	0.0961	9.8556	0	9.86
0.0003	0.9549	0.0465	0.0098	2.9400	0.1050	0.1184	9.8381	0	9.84
0.0003	1.0610	0.0574	0.0109	3.0450	0.1050	0.1426	9.8417	0	9.84
0.0003	1.1671	0.0694	0.0120	3.1500	0.1050	0.1689	9.8684	0	9.87
0.0003	1.2732	0.0826	0.0132	3.2550	0.1050	0.1970	9.9202	0	9.92
0.0005	0.8828	0.0397	-0.0429	3.3600	0.1050	0.0783	9.9990	0	10.00
0.0005	0.9507	0.0461	0.0063	3.4650	0.1050	0.0893	10.0152	0	10.02
0.0005	1.0186	0.0529	0.0068	3.5700	0.1050	0.1008	9.9931	0	9.99
0.0005	1.0865	0.0602	0.0073	3.6750	0.1050	0.1131	9.9821	0	9.98
0.0005	1.1544	0.0679	0.0078	3.7800	0.1050	0.1259	9.9829	0	9.98
0.0005	1.2223	0.0761	0.0082	3.8800	0.1000	0.4487	9.9960	0	10.00
0.0005	1.2902	0.0848	0.0087	3.8800	0.0000	0.1532	10.3365	0	10.34
0.0008	0.8289	0.0350	-0.0498	3.9900	0.1100	0.0517	10.4810	0	10.48
0.0008	0.8704	0.0386	0.0036	4.1000	0.1100	0.0564	10.4725	0	10.47
0.0008	0.9118	0.0424	0.0038	4.2100	0.1100	0.0612	10.4153	0	10.42
0.0008	0.9533	0.0463	0.0039	4.3200	0.1100	0.0662	10.3627	0	10.36
0.0013	0.6366	0.0207	-0.0257	4.4300	0.1100	0.0246	10.3150	0	10.31
0.0013	0.6631	0.0224	0.0018	4.5400	0.1100	0.0265	10.2553	0	10.26
0.0013	0.6897	0.0242	0.0018	4.6500	0.1100	0.0284	10.1700	0	10.17
0.0013	0.7162	0.0261	0.0019	4.7700	0.1200	0.0354	10.0865	0	10.09

10.0000

Description ManE1-F9	Points	Flow Rate in sub main pipe		General Exponential					Calculated Internal Diameter of Manifold		Selected Manifold Diameter	
Symbol		**Q**		**l**	**b**	**p**	**r**	**assume hf**	**di**	**di**	**do**	**di**
Units		**l/hr**	**m^3/s**						**m**	**mm**	**mm**	**mm**
end of last lateral in 1a	1	2	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0145	14.5	14.5	14.5
Class 6 20mm	2	120	0.0000	1.8	0.00089	1.77	4.77	0.015	0.0136	13.6466	20	20
	3	240	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0176	17.6493	20	20
	4	360	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0205	20.5149	20	20
	5	480	0.0001	1.8	0.00089	1.77	4.77	0.015	0.0228	22.8260	20	20
	6	600	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0248	24.7965	20	20
	7	720	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0265	26.5321	20	20
	8	840	0.0002	1.8	0.00089	1.77	4.77	0.015	0.0281	28.0940	20	20
	9	960	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0295	29.5212	20	20
	10	1080	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0308	30.8400	20	20
	11	1200	0.0003	1.8	0.00089	1.77	4.77	0.015	0.0321	32.0696	20	20
	12	1320	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0332	33.2241	20	20
	13	1440	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0343	34.3143	20	20
	14	1560	0.0004	1.8	0.00089	1.77	4.77	0.015	0.0353	35.3488	20	20
	15	1680	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0363	36.3343	20	20
Class 6 25mm	16	1800	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0373	37.2765	25	25
	17	1920	0.0005	1.8	0.00089	1.77	4.77	0.015	0.0382	38.1800	25	25
	18	2040	0.0006	1.8	0.00089	1.77	4.77	0.015	0.0390	39.0487	25	25
	19	2160	0.0006	5.8	0.00089	1.77	4.77	0.015	0.0510	50.9740	25	25
	20	2280	0.0006	1.8	0.00089	1.77	4.77	0.015	0.0407	40.6940	25	25
	21	2400	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0415	41.4760	25	25
Class 6 32mm	22	2520	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0422	42.2337	32	32
	23	2640	0.0007	1.8	0.00089	1.77	4.77	0.015	0.0430	42.9691	32	32
	24	2760	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0437	43.6837	32	32
	25	2880	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0444	44.3791	32	32
Class 6 40mm	26	3000	0.0008	1.8	0.00089	1.77	4.77	0.015	0.0451	45.0564	40	40
	27	3120	0.0009	1.8	0.00089	1.77	4.77	0.015	0.0457	45.7170	40	40
	28	3240	0.0009	2.1	0.00089	1.77	4.77	0.015	0.0479	47.8844	40	40

Area of pipe	Velocity	Velocity Head	Velocity Head Loss	Gravitational head	Gravitational Head loss	Calculated Head Loss - manifold	Pressure	Head Loss - lateral	Check End Pressure in lateral
A	v	v^2/2g	(vj^2/2g)-(vi^2/2g)	h	hj-hi	hf	P	hf	Pe
m^2	m/s	m	m	m	m	m	m	m	m
0.0002	0	0	0	0	0	0	5.0	0	5
0.0003	0.1061	0.0006	0.0006	0.8800	0.8800	0.0024	11.0038	0	11.00
0.0003	0.2122	0.0023	0.0017	0.9670	0.0870	0.0083	10.1257	0	10.13
0.0003	0.3183	0.0052	0.0029	1.0540	0.0870	0.0169	10.0452	0	10.05
0.0003	0.4244	0.0092	0.0040	1.1410	0.0870	0.0282	9.9723	0	9.97
0.0003	0.5305	0.0143	0.0052	1.2280	0.0870	0.0418	9.9094	0	9.91
0.0003	0.6366	0.0207	0.0063	1.3150	0.0870	0.0578	9.8591	0	9.86
0.0003	0.7427	0.0281	0.0075	1.4020	0.0870	0.0759	9.8235	0	9.82
0.0003	0.8488	0.0367	0.0086	1.4890	0.0870	0.0961	9.8049	0	9.80
0.0003	0.9549	0.0465	0.0098	1.5760	0.0870	0.1184	9.8054	0	9.81
0.0003	1.0610	0.0574	0.0109	1.6630	0.0870	0.1426	9.8270	0	9.83
0.0003	1.1671	0.0694	0.0120	1.7500	0.0870	0.1689	9.8718	0	9.87
0.0003	1.2732	0.0826	0.0132	1.8370	0.0870	0.1970	9.9416	0	9.94
0.0003	1.3793	0.0970	0.0143	1.9240	0.0870	0.2269	10.0384	0	10.04
0.0003	1.4854	0.1125	0.0155	2.0110	0.0870	0.2588	10.1640	0	10.16
0.0005	1.0186	0.0529	-0.0596	2.0980	0.0870	0.1008	10.3202	0	10.32
0.0005	1.0865	0.0602	0.0073	2.1850	0.0870	0.1131	10.3937	0	10.39
0.0005	1.1544	0.0679	0.0078	2.2720	0.0870	0.1259	10.4124	0	10.41
0.0005	1.2223	0.0761	0.0082	2.5400	0.2680	0.4487	10.4435	0	10.44
0.0005	1.2902	0.0848	0.0087	3.3800	0.8400	0.1532	10.6160	0	10.62
0.0005	1.3581	0.0940	0.0092	3.4253	0.0453	0.1678	9.9206	0	9.92
0.0008	0.8704	0.0386	-0.0554	3.4706	0.0453	0.0564	10.0339	0	10.03
0.0008	0.9118	0.0424	0.0038	3.5159	0.0453	0.0612	10.1003	0	10.10
0.0008	0.9533	0.0463	0.0039	3.5612	0.0453	0.0662	10.1125	0	10.11
0.0008	0.9947	0.0504	0.0041	3.6065	0.0453	0.0714	10.1294	0	10.13
0.0013	0.6631	0.0224	-0.0280	3.6518	0.0453	0.0265	10.1514	0	10.15
0.0013	0.6897	0.0242	0.0018	3.6971	0.0453	0.0284	10.1606	0	10.16
0.0013	0.7162	0.0261	0.0019	3.7424	0.0453	0.0354	10.1418	0	10.14

10.1300

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Lateral Slope 1:	Pressure at Emitter (kPa)
		Lateral Slope 1 :						
End Emitter	9.54							30.000
1	9.54	0.000159	1.8	0.025	0.324	0.011	50.000	29.745
2	19.08	0.000318	1.8	0.032	0.395	0.011	50.000	29.499
3	28.62	0.000477	1.8	0.032	0.593	0.024	50.000	29.380
4	38.16	0.000636	1.8	0.032	0.791	0.041	50.000	29.432
5	47.7	0.000795	1.8	0.04	0.633	0.021	50.000	29.282
6	57.24	0.000954	1.8	0.04	0.759	0.029	50.000	29.216
7	66.78	0.001113	1.8	0.04	0.886	0.039	50.000	29.247
8	76.32	0.001272	1.8	0.04	1.012	0.050	50.000	29.388
9	85.86	0.001431	1.8	0.05	0.729	0.021	50.000	29.238
10	95.4	0.00159	1.8	0.05	0.810	0.026	50.000	29.133
11	104.94	0.001749	1.8	0.05	0.891	0.030	50.000	29.078
12	114.48	0.001908	1.8	0.05	0.972	0.036	50.000	29.076
13	124.02	0.002067	1.8	0.05	1.053	0.042	50.000	29.131
14	133.56	0.002226	1.8	0.05	1.134	0.048	50.000	29.247
15	143.1	0.002385	1.8	0.05	1.215	0.054	50.000	29.428
16	152.64	0.002544	1.8	0.065	0.767	0.017	50.000	29.238
17	162.18	0.002703	1.8	0.065	0.815	0.019	50.000	29.068
18	171.72	0.002862	1.8	0.065	0.862	0.021	50.000	28.920
19	181.26	0.003021	1.8	0.065	0.910	0.023	50.000	28.793
20	190.8	0.00318	1.8	0.065	0.958	0.026	50.000	28.690
21	200.34	0.003339	1.8	0.065	1.006	0.028	50.000	28.611
22	209.88	0.003498	1.8	0.065	1.054	0.031	50.000	28.558
23	219.42	0.003657	1.8	0.065	1.102	0.033	50.000	28.530
24	228.96	0.003816	1.8	0.065	1.150	0.036	50.000	28.530
25	238.5	0.003975	1.8	0.065	1.198	0.039	50.000	28.559
26	248.04	0.004134	1.8	0.065	1.246	0.042	50.000	28.616
27	257.58	0.004293	1.8	0.065	1.294	0.045	50.000	28.704
28	267.12	0.004452	1.8	0.065	1.342	0.048	50.000	28.823
29	276.66	0.004611	1.8	0.065	1.390	0.051	50.000	28.974
30	286.2	0.00477	1.8	0.065	1.437	0.054	50.000	29.158
31	295.74	0.004929	1.8	0.065	1.485	0.058	50.000	29.377
32	305.28	0.005088	1.8	0.065	1.533	0.061	50.000	29.630
33	314.82	0.005247	1.8	0.065	1.581	0.065	50.000	29.919
34	324.36	0.005406	1.8	0.065	1.629	0.069	50.000	30.246
35	333.9	0.005565	1.8	0.065	1.677	0.072	50.000	30.610
36	343.44	0.005724	1.8	0.065	1.725	0.076	50.000	31.013
37	352.98	0.005883	1.8	0.065	1.773	0.080	50.000	31.455
38	362.52		1.8					

Pressure at Emitter (m)	Pressure in Lateral P1 (Pa)	Required Discharge (m3/s)	Diameter of emmitter pipe (m)	Length Emmitter pipe (cm)	Diameter o lateral d1 m	Area emmi pipe A2 m2
3.000	30000.00	0.000159	0.01	46.09	0.025	7.85E-05
2.975	29745.06	0.000159	0.01	45.67	0.025	7.85E-05
2.950	29499.01	0.000159	0.01	45.21	0.032	7.85E-05
2.938	29380.48	0.000159	0.01	45.02	0.032	7.85E-05
2.943	29431.86	0.000159	0.01	45.10	0.032	7.85E-05
2.928	29281.61	0.000159	0.01	44.83	0.04	7.85E-05
2.922	29215.60	0.000159	0.01	44.73	0.04	7.85E-05
2.925	29246.74	0.000159	0.01	44.78	0.04	7.85E-05
2.939	29387.61	0.000159	0.01	45.01	0.04	7.85E-05
2.924	29237.71	0.000159	0.01	44.75	0.05	7.85E-05
2.913	29133.09	0.000159	0.01	44.58	0.05	7.85E-05
2.908	29077.77	0.000159	0.01	44.49	0.05	7.85E-05
2.908	29075.72	0.000159	0.01	44.49	0.05	7.85E-05
2.913	29130.86	0.000159	0.01	44.58	0.05	7.85E-05
2.925	29247.08	0.000159	0.01	44.77	0.05	7.85E-05
2.943	29428.21	0.000159	0.01	45.07	0.05	7.85E-05
2.924	29238.12	0.000159	0.01	44.75	0.065	7.85E-05
2.907	29068.22	0.000159	0.01	44.47	0.065	7.85E-05
2.892	28919.55	0.000159	0.01	44.23	0.065	7.85E-05
2.879	28793.13	0.000159	0.01	44.02	0.065	7.85E-05
2.869	28689.99	0.000159	0.01	43.85	0.065	7.85E-05
2.861	28611.14	0.000159	0.01	43.72	0.065	7.85E-05
2.856	28557.58	0.000159	0.01	43.63	0.065	7.85E-05
2.853	28530.33	0.000159	0.01	43.59	0.065	7.85E-05
2.853	28530.36	0.000159	0.01	43.59	0.065	7.85E-05
2.856	28558.66	0.000159	0.01	43.63	0.065	7.85E-05
2.862	28616.22	0.000159	0.01	43.73	0.065	7.85E-05
2.870	28704.01	0.000159	0.01	43.87	0.065	7.85E-05
2.882	28823.00	0.000159	0.01	44.07	0.065	7.85E-05
2.897	28974.15	0.000159	0.01	44.32	0.065	7.85E-05
2.916	29158.42	0.000159	0.01	44.62	0.065	7.85E-05
2.938	29376.77	0.000159	0.01	44.98	0.065	7.85E-05
2.963	29630.15	0.000159	0.01	45.40	0.065	7.85E-05
2.992	29919.49	0.000159	0.01	45.87	0.065	7.85E-05
3.025	30245.75	0.000159	0.01	46.41	0.065	7.85E-05
3.061	30609.85	0.000159	0.01	47.01	0.065	7.85E-05
3.101	31012.74	0.000159	0.01	47.67	0.065	7.85E-05
3.146	31455.34	0.000159	0.01	48.40	0.065	7.85E-05

Area lateral A1 m2	Velocity in emiter pipe V2 m/s	Velocity in lateral V1 m/s	Reynolds N emiter pipe	f factor	P1/pg	v12/2g	z1
0.000491	2.024450876	0.323912	20237.63	0.296494	3.058103976	0.005348	0
0.000491	2.024450876	0.323912	20237.63	0.296494	3.032115868	0.005348	0
0.000804	2.024450876	0.1977	20237.63	0.296494	3.007034928	0.001992	0
0.000804	2.024450876	0.1977	20237.63	0.296494	2.994952074	0.001992	0
0.000804	2.024450876	0.1977	20237.63	0.296494	3.000189732	0.001992	0
0.001257	2.024450876	0.126528	20237.63	0.296494	2.984873464	0.000816	0
0.001257	2.024450876	0.126528	20237.63	0.296494	2.978145149	0.000816	0
0.001257	2.024450876	0.126528	20237.63	0.296494	2.981318864	0.000816	0
0.001257	2.024450876	0.126528	20237.63	0.296494	2.995678913	0.000816	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.980399071	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.969733955	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.964094386	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.96388542	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.969506922	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.981354044	0.000334	0
0.001963	2.024450876	0.080978	20237.63	0.296494	2.999817621	0.000334	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.980440427	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.963121245	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.947965882	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.935079253	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.924565437	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.916527725	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.911068665	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.908290099	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.908293204	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.91117852	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.91704598	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.925994941	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.938124204	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.953532041	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.972316215	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	2.994573999	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.020402194	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.04989715	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.083154775	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.120270558	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.161339576	0.000117	0
0.003318	2.024450876	0.047916	20237.63	0.296494	3.206456514	0.000117	0

E1	P2/pg	v22/2g	z1	E2	flv22/2gd	l
					xl	m
3.063452	0	0.208889	0	0.208889	6.193432	0.460902
3.037463	0	0.208889	0	0.208889	6.193432	0.456706
3.009027	0	0.208889	0	0.208889	6.193432	0.452114
2.996944	0	0.208889	0	0.208889	6.193432	0.450163
3.002182	0	0.208889	0	0.208889	6.193432	0.451009
2.985689	0	0.208889	0	0.208889	6.193432	0.448346
2.978961	0	0.208889	0	0.208889	6.193432	0.44726
2.982135	0	0.208889	0	0.208889	6.193432	0.447772
2.996495	0	0.208889	0	0.208889	6.193432	0.450091
2.980733	0	0.208889	0	0.208889	6.193432	0.447546
2.970068	0	0.208889	0	0.208889	6.193432	0.445824
2.964429	0	0.208889	0	0.208889	6.193432	0.444913
2.96422	0	0.208889	0	0.208889	6.193432	0.444879
2.969841	0	0.208889	0	0.208889	6.193432	0.445787
2.981688	0	0.208889	0	0.208889	6.193432	0.4477
3.000152	0	0.208889	0	0.208889	6.193432	0.450681
2.980557	0	0.208889	0	0.208889	6.193432	0.447517
2.963238	0	0.208889	0	0.208889	6.193432	0.444721
2.948083	0	0.208889	0	0.208889	6.193432	0.442274
2.935196	0	0.208889	0	0.208889	6.193432	0.440193
2.924682	0	0.208889	0	0.208889	6.193432	0.438496
2.916645	0	0.208889	0	0.208889	6.193432	0.437198
2.911186	0	0.208889	0	0.208889	6.193432	0.436317
2.908407	0	0.208889	0	0.208889	6.193432	0.435868
2.90841	0	0.208889	0	0.208889	6.193432	0.435868
2.911296	0	0.208889	0	0.208889	6.193432	0.436334
2.917163	0	0.208889	0	0.208889	6.193432	0.437282
2.926112	0	0.208889	0	0.208889	6.193432	0.438727
2.938241	0	0.208889	0	0.208889	6.193432	0.440685
2.953649	0	0.208889	0	0.208889	6.193432	0.443173
2.972433	0	0.208889	0	0.208889	6.193432	0.446206
2.994691	0	0.208889	0	0.208889	6.193432	0.449799
3.020519	0	0.208889	0	0.208889	6.193432	0.45397
3.050014	0	0.208889	0	0.208889	6.193432	0.458732
3.083272	0	0.208889	0	0.208889	6.193432	0.464102
3.120388	0	0.208889	0	0.208889	6.193432	0.470095
3.161457	0	0.208889	0	0.208889	6.193432	0.476726
3.206574	0	0.208889	0	0.208889	6.193432	0.48401

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Lateral Slope 1:	Pressure at Emitter (kPa)
		Lateral Slope 1 :						
End Emitter	11.33							30.000
1	11.33	0.000189	1.8	0.04	0.150	0.001	50.000	29.655
2	22.66	0.000378	1.8	0.04	0.301	0.005	50.000	29.347
3	33.99	0.000567	1.8	0.04	0.451	0.011	50.000	29.099
4	45.32	0.000755	1.8	0.04	0.601	0.019	50.000	28.930
5	56.65	0.000944	1.8	0.04	0.751	0.029	50.000	28.859
6	67.98	0.001133	1.8	0.04	0.902	0.040	50.000	28.903
7	79.31	0.001322	1.8	0.04	1.052	0.054	50.000	29.081
8	90.64	0.001511	1.8	0.05	0.769	0.023	50.000	28.953
9	101.97	0.0017	1.8	0.05	0.866	0.029	50.000	28.882
10	113.3	0.001888	1.8	0.05	0.962	0.035	50.000	28.873
11	124.63	0.002077	1.8	0.05	1.058	0.042	50.000	28.932
12	135.96	0.002266	1.8	0.05	1.154	0.049	50.000	29.064
13	147.29	0.002455	1.8	0.05	1.250	0.057	50.000	29.275
14	158.62	0.002644	1.8	0.065	0.797	0.018	50.000	29.097
15	169.95	0.002833	1.8	0.065	0.854	0.021	50.000	28.945
16	181.28	0.003021	1.8	0.065	0.911	0.023	50.000	28.818
17	192.61	0.00321	1.8	0.065	0.967	0.026	50.000	28.720
18	203.94	0.003399	1.8	0.065	1.024	0.029	50.000	28.650
19	215.27	0.003588	1.8	0.065	1.081	0.032	50.000	28.612
20	226.6	0.003777	1.8	0.065	1.138	0.035	50.000	28.605
21	237.93	0.003966	1.8	0.065	1.195	0.039	50.000	28.631
22	249.26	0.004154	1.8	0.065	1.252	0.042	50.000	28.693
23	260.59	0.004343	1.8	0.065	1.309	0.046	50.000	28.790
24	271.92	0.004532	1.8	0.065	1.366	0.050	50.000	28.925
25	283.25	0.004721	1.8	0.065	1.423	0.053	50.000	29.099
26	294.58	0.00491	1.8	0.065	1.480	0.057	50.000	29.313
27	305.91	0.005099	1.8	0.065	1.536	0.062	50.000	29.569
28	317.24	0.005287	1.8	0.065	1.593	0.066	50.000	29.868
29	328.57	0.005476	1.8	0.065	1.650	0.070	50.000	30.211
30	339.9	0.005665	1.8	0.065	1.707	0.075	50.000	30.599
31	351.23	0.005854	1.8	0.065	1.764	0.080	50.000	31.034
32	362.56	0.006043	1.8	0.065	1.821	0.084	50.000	31.518

Pressure at Emitter (m)	Pressure in Lateral P1 (Pa)	Required Discharge ((m3/s)	Diameter of emmitter pipe (m)	Length Emmitter pipe (cm)	Diameter o lateral d1 m	Area emmi pipe A2 m2
3.000	30000.00	0.000189	0.01	31.77	0.04	7.85E-05
2.965	29654.64	0.000189	0.01	31.36	0.04	7.85E-05
2.935	29347.49	0.000189	0.01	31.00	0.04	7.85E-05
2.910	29099.47	0.000189	0.01	30.71	0.04	7.85E-05
2.893	28930.25	0.000189	0.01	30.51	0.04	7.85E-05
2.886	28858.65	0.000189	0.01	30.43	0.04	7.85E-05
2.890	28902.90	0.000189	0.01	30.48	0.04	7.85E-05
2.908	29080.72	0.000189	0.01	30.69	0.04	7.85E-05
2.895	28953.00	0.000189	0.01	30.53	0.05	7.85E-05
2.888	28881.90	0.000189	0.01	30.45	0.05	7.85E-05
2.887	28873.05	0.000189	0.01	30.44	0.05	7.85E-05
2.893	28931.98	0.000189	0.01	30.51	0.05	7.85E-05
2.906	29064.17	0.000189	0.01	30.66	0.05	7.85E-05
2.928	29275.01	0.000189	0.01	30.91	0.05	7.85E-05
2.910	29097.45	0.000189	0.01	30.70	0.065	7.85E-05
2.894	28944.76	0.000189	0.01	30.52	0.065	7.85E-05
2.882	28818.39	0.000189	0.01	30.37	0.065	7.85E-05
2.872	28719.78	0.000189	0.01	30.26	0.065	7.85E-05
2.865	28650.36	0.000189	0.01	30.17	0.065	7.85E-05
2.861	28611.54	0.000189	0.01	30.13	0.065	7.85E-05
2.860	28604.73	0.000189	0.01	30.12	0.065	7.85E-05
2.863	28631.32	0.000189	0.01	30.15	0.065	7.85E-05
2.869	28692.69	0.000189	0.01	30.22	0.065	7.85E-05
2.879	28790.22	0.000189	0.01	30.34	0.065	7.85E-05
2.893	28925.27	0.000189	0.01	30.50	0.065	7.85E-05
2.910	29099.20	0.000189	0.01	30.70	0.065	7.85E-05
2.931	29313.35	0.000189	0.01	30.95	0.065	7.85E-05
2.957	29569.07	0.000189	0.01	31.25	0.065	7.85E-05
2.987	29867.69	0.000189	0.01	31.60	0.065	7.85E-05
3.021	30210.54	0.000189	0.01	32.00	0.065	7.85E-05
3.060	30598.93	0.000189	0.01	32.46	0.065	7.85E-05
3.103	31034.17	0.000189	0.01	32.97	0.065	7.85E-05
3.152	31517.57	0.000189	0.01	33.53	0.065	7.85E-05

Area lateral A1 m2	Velocity in emiter pipe V2 m/s	Velocity in lateral V1 m/s	Reynolds N emiter pipe	f factor	P1/pg	v12/2g	z1
0.001257	2.404300674	0.150269	24034.83	0.295379	3.058103976	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	3.022898991	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.991588817	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.966306517	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.94905662	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.941758728	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.946269474	0.001151	0
0.001257	2.404300674	0.150269	24034.83	0.295379	2.964395748	0.001151	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.951376369	0.000471	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.944128563	0.000471	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.943226116	0.000471	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.949233914	0.000471	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.96270892	0.000471	0
0.001963	2.404300674	0.096172	24034.83	0.295379	2.984200959	0.000471	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.966101373	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.950536594	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.937654831	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.927602884	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.92052624	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.916569159	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.915874752	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.918585047	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.924841049	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.934782796	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.948549405	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.966279122	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	2.988109359	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.014176733	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.044617098	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.07956558	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.119156606	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.163523927	0.000165	0
0.003318	2.404300674	0.056907	24034.83	0.295379	3.212800649	0.000165	0

E1	P2/pg	v22/2g	z1	E2	flv22/2gd	l
					xl	m
3.059255	0	0.294631	0	0.294631	8.702787	0.317671
3.02405	0	0.294631	0	0.294631	8.702787	0.313626
2.99274	0	0.294631	0	0.294631	8.702787	0.310028
2.967457	0	0.294631	0	0.294631	8.702787	0.307123
2.950208	0	0.294631	0	0.294631	8.702787	0.305141
2.94291	0	0.294631	0	0.294631	8.702787	0.304302
2.94742	0	0.294631	0	0.294631	8.702787	0.304821
2.965547	0	0.294631	0	0.294631	8.702787	0.306903
2.951848	0	0.294631	0	0.294631	8.702787	0.305329
2.9446	0	0.294631	0	0.294631	8.702787	0.304497
2.943698	0	0.294631	0	0.294631	8.702787	0.304393
2.949705	0	0.294631	0	0.294631	8.702787	0.305083
2.96318	0	0.294631	0	0.294631	8.702787	0.306632
2.984672	0	0.294631	0	0.294631	8.702787	0.309101
2.966266	0	0.294631	0	0.294631	8.702787	0.306986
2.950702	0	0.294631	0	0.294631	8.702787	0.305198
2.93782	0	0.294631	0	0.294631	8.702787	0.303718
2.927768	0	0.294631	0	0.294631	8.702787	0.302562
2.920691	0	0.294631	0	0.294631	8.702787	0.301749
2.916734	0	0.294631	0	0.294631	8.702787	0.301295
2.91604	0	0.294631	0	0.294631	8.702787	0.301215
2.91875	0	0.294631	0	0.294631	8.702787	0.301526
2.925006	0	0.294631	0	0.294631	8.702787	0.302245
2.934948	0	0.294631	0	0.294631	8.702787	0.303387
2.948714	0	0.294631	0	0.294631	8.702787	0.304969
2.966444	0	0.294631	0	0.294631	8.702787	0.307007
2.988274	0	0.294631	0	0.294631	8.702787	0.309515
3.014342	0	0.294631	0	0.294631	8.702787	0.31251
3.044782	0	0.294631	0	0.294631	8.702787	0.316008
3.079731	0	0.294631	0	0.294631	8.702787	0.320024
3.119322	0	0.294631	0	0.294631	8.702787	0.324573
3.163689	0	0.294631	0	0.294631	8.702787	0.329671
3.212966	0	0.294631	0	0.294631	8.702787	0.335333

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Emitter Number (starting from bottom end)	Q in lateral segment (l/min)	Q in lateral segment (m3/s)	L of lateral segment (m)	Diameter of lateral segment (m)	Velocity in lateral segment (m/s)	Hf (HW) (m)	Lateral Slope 1:	Pressure at Emitter (kPa)
		Lateral Slope 1 :						
End Emitter	14.1							30.000
1	14.1	0.000235	1.8	0.04	0.187	0.002	50.000	29.662
2	28.2	0.00047	1.8	0.04	0.374	0.008	50.000	29.381
3	42.3	0.000705	1.8	0.04	0.561	0.017	50.000	29.189
4	56.4	0.00094	1.8	0.04	0.748	0.029	50.000	29.115
5	70.5	0.001175	1.8	0.05	0.598	0.015	50.000	28.901
6	84.6	0.00141	1.8	0.05	0.718	0.020	50.000	28.745
7	98.7	0.001645	1.8	0.05	0.838	0.027	50.000	28.657
8	112.8	0.00188	1.8	0.05	0.957	0.035	50.000	28.646
9	126.9	0.002115	1.8	0.05	1.077	0.043	50.000	28.719
10	141	0.00235	1.8	0.05	1.197	0.053	50.000	28.885
11	155.1	0.002585	1.8	0.05	1.317	0.063	50.000	29.154
12	169.2	0.00282	1.8	0.065	0.850	0.021	50.000	28.999
13	183.3	0.003055	1.8	0.065	0.921	0.024	50.000	28.878
14	197.4	0.00329	1.8	0.065	0.991	0.027	50.000	28.791
15	211.5	0.003525	1.8	0.065	1.062	0.031	50.000	28.742
16	225.6	0.00376	1.8	0.065	1.133	0.035	50.000	28.732
17	239.7	0.003995	1.8	0.065	1.204	0.039	50.000	28.764
18	253.8	0.00423	1.8	0.065	1.275	0.044	50.000	28.840
19	267.9	0.004465	1.8	0.065	1.346	0.048	50.000	28.962
20	282	0.0047	1.8	0.065	1.416	0.053	50.000	29.131
21	296.1	0.004935	1.8	0.065	1.487	0.058	50.000	29.351
22	310.2	0.00517	1.8	0.065	1.558	0.063	50.000	29.623
23	324.3	0.005405	1.8	0.065	1.629	0.069	50.000	29.949
24	338.4	0.00564	1.8	0.065	1.700	0.074	50.000	30.331
25	352.5	0.005875	1.8	0.065	1.770	0.080	50.000	30.771
26	366.6	0.00611	1.8	0.065	1.841	0.086	50.000	31.272
27	380.7			0.065				

Pressure at Emitter (m)	Pressure in Lateral P1 (Pa)	Required Discharge ((m3/s)	Diameter of emmitter pipe (m)	Length Emmitter pipe (cm)	Diameter o lateral d1 m	Area emmi pipe A2 m2
3.000	30000.00	0.000235	0.01	19.41	0.04	7.85E-05
2.966	29661.95	0.000235	0.01	19.15	0.04	7.85E-05
2.938	29381.19	0.000235	0.01	18.94	0.04	7.85E-05
2.919	29189.09	0.000235	0.01	18.79	0.04	7.85E-05
2.912	29115.15	0.000235	0.01	18.73	0.04	7.85E-05
2.890	28901.00	0.000235	0.01	18.56	0.05	7.85E-05
2.875	28745.43	0.000235	0.01	18.44	0.05	7.85E-05
2.866	28657.40	0.000235	0.01	18.38	0.05	7.85E-05
2.865	28645.69	0.000235	0.01	18.37	0.05	7.85E-05
2.872	28718.86	0.000235	0.01	18.42	0.05	7.85E-05
2.889	28885.38	0.000235	0.01	18.55	0.05	7.85E-05
2.915	29153.53	0.000235	0.01	18.75	0.05	7.85E-05
2.900	28999.15	0.000235	0.01	18.63	0.065	7.85E-05
2.888	28877.63	0.000235	0.01	18.54	0.065	7.85E-05
2.879	28791.18	0.000235	0.01	18.48	0.065	7.85E-05
2.874	28742.02	0.000235	0.01	18.44	0.065	7.85E-05
2.873	28732.33	0.000235	0.01	18.43	0.065	7.85E-05
2.876	28764.26	0.000235	0.01	18.46	0.065	7.85E-05
2.884	28839.96	0.000235	0.01	18.51	0.065	7.85E-05
2.896	28961.54	0.000235	0.01	18.61	0.065	7.85E-05
2.913	29131.11	0.000235	0.01	18.73	0.065	7.85E-05
2.935	29350.77	0.000235	0.01	18.90	0.065	7.85E-05
2.962	29622.57	0.000235	0.01	19.11	0.065	7.85E-05
2.995	29948.60	0.000235	0.01	19.36	0.065	7.85E-05
3.033	30330.88	0.000235	0.01	19.65	0.065	7.85E-05
3.077	30771.46	0.000235	0.01	19.98	0.065	7.85E-05
3.127	31272.35	0.000235	0.01	20.36	0.065	7.85E-05

Area lateral A1 m2	Velocity in emiter pipe V2 m/s	Velocity in lateral V1 m/s	Reynolds N emiter pipe	f factor	P1/pg	v12/2g	z1
0.001257	2.99211293	0.187007	29910.96	0.294029	3.058103976	0.001782	0
0.001257	2.99211293	0.187007	29910.96	0.294029	3.02364424	0.001782	0
0.001257	2.99211293	0.187007	29910.96	0.294029	2.995024417	0.001782	0
0.001257	2.99211293	0.187007	29910.96	0.294029	2.97544284	0.001782	0
0.001257	2.99211293	0.187007	29910.96	0.294029	2.967905119	0.001782	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.946075181	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.930216894	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.921244006	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.920049558	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.927509057	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.944482842	0.00073	0
0.001963	2.99211293	0.119685	29910.96	0.294029	2.971817909	0.00073	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.956080739	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.943692783	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.93488103	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.929869988	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.928881883	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.932136829	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.939852969	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.95224661	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.969532333	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	2.991923094	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	3.01963032	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	3.052863981	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	3.091832676	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	3.136743689	0.000256	0
0.003318	2.99211293	0.070819	29910.96	0.294029	3.187803056	0.000256	0

E1	P2/pg	v22/2g	z1	E2	flv22/2gd	l
					xl	m
3.059886	0	0.456307	0	0.456307	13.41673	0.194055
3.025427	0	0.456307	0	0.456307	13.41673	0.191486
2.996807	0	0.456307	0	0.456307	13.41673	0.189353
2.977225	0	0.456307	0	0.456307	13.41673	0.187894
2.969688	0	0.456307	0	0.456307	13.41673	0.187332
2.946805	0	0.456307	0	0.456307	13.41673	0.185626
2.930947	0	0.456307	0	0.456307	13.41673	0.184444
2.921974	0	0.456307	0	0.456307	13.41673	0.183776
2.92078	0	0.456307	0	0.456307	13.41673	0.183687
2.928239	0	0.456307	0	0.456307	13.41673	0.184243
2.945213	0	0.456307	0	0.456307	13.41673	0.185508
2.972548	0	0.456307	0	0.456307	13.41673	0.187545
2.956336	0	0.456307	0	0.456307	13.41673	0.186337
2.943948	0	0.456307	0	0.456307	13.41673	0.185413
2.935137	0	0.456307	0	0.456307	13.41673	0.184757
2.930126	0	0.456307	0	0.456307	13.41673	0.184383
2.929138	0	0.456307	0	0.456307	13.41673	0.18431
2.932392	0	0.456307	0	0.456307	13.41673	0.184552
2.940109	0	0.456307	0	0.456307	13.41673	0.185127
2.952502	0	0.456307	0	0.456307	13.41673	0.186051
2.969788	0	0.456307	0	0.456307	13.41673	0.187339
2.992179	0	0.456307	0	0.456307	13.41673	0.189008
3.019886	0	0.456307	0	0.456307	13.41673	0.191073
3.05312	0	0.456307	0	0.456307	13.41673	0.19355
3.092088	0	0.456307	0	0.456307	13.41673	0.196455
3.136999	0	0.456307	0	0.456307	13.41673	0.199802
3.188059	0	0.456307	0	0.456307	13.41673	0.203608

Gravity m/s2	Density kg/m3	Kinematic Viscosity 20C mm2/s
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034
9.81	1000	1.00034

Lateral Number (starting from bottom end)	Q in sub main segment (l/min)	Q in sub main segment (m3/s)	L in sub main segment (m)	Diameter of sub main segment (m)	Velocity in sub main segment (m/s)	Hf (HW) (m)	Valve Loss 0.700 (m)
End Lateral	362.5						
1	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
2	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
3	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
4	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
5	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
6	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
7	362.5	0.00604167	31.25	0.08	1.202	0.532	0.300
	362.5	0.00604167	3	0.08	1.202	0.051	

Submain Slope 1:	Pressure at Emitter (kPa)	Pressure at Emitter (m)
	40.000	4.000
250.000	47.074	4.707
250.000	54.148	5.415
250.000	61.223	6.122
250.000	68.297	6.830
250.000	75.371	7.537
250.000	79.445	7.945
250.000	83.519	8.352
250.000	83.910	8.391

Lateral Number (starting from bottom end)	Q in sub mai segment (l/min)	Q in sub mai segment (m3/s)	L in sub mai segment (m)	Diameter of sub mai segment (m)	Velocity in sub main segment (m/s)	Hf (HW) (m)	Valve Loss 0.700 (m)	Submain Slope 1:
End Lateral	362.6							
1	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
2	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
3	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
4	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
5	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
6	362.6	0.006043	35.71429	0.08	1.202	0.609	0.300	250.000
	362.6	0.006043	3	0.08	1.202	0.051		250.000

Pressure at Emitter (kPa)	Pressure at Emitter (m)
40.000	4.000
47.659	4.766
55.319	5.532
62.978	6.298
70.637	7.064
78.296	7.830
82.956	8.296
83.347	8.335

Lateral Number (starting from bottom end)	Q in sub main segment (l/min)	Q in sub main segment (m3/s)	L in sub main segment (m)	Diameter of sub main segment (m)	Velocity in sub main segment (m/s)	Hf (HW) (m)	Valve Loss 0.700 (m)
End Lateral	380.7						
1	380.7	0.006345	41.66666667	0.08	1.262	0.777	0.300
2	380.7	0.006345	41.66666667	0.08	1.262	0.777	0.300
3	380.7	0.006345	41.66666667	0.08	1.262	0.777	0.300
4	380.7	0.006345	41.66666667	0.08	1.262	0.777	0.300
5	380.7	0.006345	41.66666667	0.08	1.262	0.777	0.300
	380.7	0.006345	3	0.08	1.262	0.056	

Submain Slope 1:	Pressure at Emitter (kPa)	Pressure at Emitter (m)
	40.000	4.000
250.000	49.106	4.911
250.000	58.213	5.821
250.000	67.319	6.732
250.000	76.426	7.643
250.000	85.532	8.553
250.000	85.972	8.597

Lateral Number (starting from bottom end)	Q in main segment (l/min)	Q in main segment (m3/s)	L in main segment (m)	Diameter of main segment (m)	Velocity in main segment (m/s)	Hf (HW) (m)	Valve Loss 0.700 (m)
End Submain	362.5						
1	362.5	0.00604167	66.7	0.084	1.090	0.896	0.500
2	362.5	0.00604167	66.7	0.084	1.090	0.896	0.500
3	362.5	0.00604167	66.7	0.084	1.090	0.896	0.500
4	362.5	0.00604167	66.7	0.084	1.090	0.896	0.500
5	362.5	0.00604167	66.7	0.084	1.090	0.896	0.500
To field bottom	362.5	0.00604167	250	0.1	0.769	1.437	0.500
To Pump	362.5	0.00604167	150	0.1	0.769	0.862	

Submain Slope 1:	Pressure at Sub main (kPa)	Pressure at Sub main (m)
	83.910	8.391
50.000	84.530	8.453
50.000	85.150	8.515
50.000	85.771	8.577
50.000	86.391	8.639
50.000	87.011	8.701
-250.000	111.377	11.138
-250.000	125.996	12.600

	Q in main segment (m^3/h)		
	21.75		
	21.75		
	21.75		
	21.75		
	21.75		
	21.75		
	21.75		

Pipe requiren	Lateral			
Option:	Pipe Size (mm)	No of Sections	No. of Laterals	Pipe Length Req. (m)
Option 1	25	1	48	86.4
	32	3	48	259.2
	40	4	48	345.6
	50	7	48	604.8
	65	22	48	1948.8
Option 2	40	7	49	617.4
	50	6	49	529.2
	65	19	49	1724.8
Option 3	40	4	48	345.6
	50	7	48	604.8
	65	15	48	1344

Pipe requiren	Sub Main			
Option:	Pipe Size (mm)	pipe length/sub	No. of Submains	Pipe Length Req. (m)
Option 1	80	220.8	6	1324.8
Option 2	80	216.1	7	1512.7
Option 3	80	209.8	8	1678.4

Piping Required (m	Cost/m [R	Cost [R]
100	3.19	319.00
300	4.42	1326.00
350	6.29	2201.50
650	10.17	6610.50
1950	15.50	30225.00
Total Cost:		40682.00
650	6.29	4088.50
550	10.17	5593.50
1750	15.50	27125.00
Total Cost:		36807.00
350	6.29	2201.50
650	10.17	6610.50
1500	15.50	23250.00
Total Cost:		32062.00

Option
Option 1
Option 2
Option 3

Piping Required (m	Cost/m	Cost [R]	Total Lateral + Sub Main Cost [R]
1350	12.31	16618.5	57300.50
1542	12.31	18982.02	55789.02
1704	12.31	20976.24	53038.24