Water and nutrient distribution during trickle irrigation on three soils

by

DIEDERICK ARNOLDIS SCHOLTZ

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Study Leader: Professor A.T.P. Bennie

DECLARATION

I hereby declare that his thesis, prepared for the degree Magister Scientiae Agriculturae, which was submitted by me to the University of the Free State, is my own work and has not been submitted to any other university.

I also agree that the University of the Free State has sole right to production of this thesis.

Signed:

Diederick Arnoldis Scholtz

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1.1 Literature study

1.1.1 Introduction

Trickle irrigation is the most common micro-irrigation method based on maintaining a partially wetted soil volume where conditions for crop growth are optimal. The ability to wet only the soil immediately around the crop allows fewer weeds to germinate and allows leaves to stay dry, inhibiting the spread of fungal diseases.

Irrigation around the world is facing increasing pressure to improve the efficiency of water use and to reduce associated environmental impacts such as rising groundwater tables, salinisation, and groundwater pollution (Bristow, Cote, Thorburn & Cook, 2000). There is also a reduction in fertilizer and pesticides needed with trickle irrigation, as pesticides are not washed from the foliage, smaller quantities may be effective and for longer periods of time.

However, the advantages must be weighed against the disadvantages of implementing a trickle irrigation system. The high initial costs of trickle irrigation necessitate a substantial return either in the form of savings in irrigation water or increased crop yields.

The design and management of trickle irrigation requires an understanding of water and solute distribution patterns, which may be described and predicted by solving the governing flow equations (Bristow *et al.*, 2000). While some guidelines have been published to help growers install, maintain and operate trickle irrigation systems (Nakayama & Bucks, 1986), there are at present few, if any, clear guidelines for designing and managing trickle irrigation systems that account for differences in soil hydraulic properties. Hence, systems are often designed to an economic optimum in terms of engineering principles, which may not produce the best environmental outcomes. There is therefore an ongoing need for assessment and continuous improvement of practical guidelines for designing and managing irrigation/fertigation systems.

The basic parameters needed for designing trickle irrigation systems are emitter discharge, inline and lateral spacing of emitters as well as crop water requirements. The movement of water in the soil is mainly affected by soil properties. Spatial variations in soil properties induce variations in wetting patterns below trickle emitters, which complicate the acquisition and interpretation of information on soil water status. Soil is frequently stratified near the surface, containing layers with markedly different water retention and water conducting properties. Stratification also affects the wetting pattern under trickle irrigation. Knowledge of soil wetting patterns under the emitter for a particular soil, is required, before deciding on the design requirements for a particular crop and climate.

In trickle irrigation, emitters apply water at a point on the soil surface. But as the infiltration does not take place at a single point of infinitesimal dimensions, water moves across the soil surface away from the emitter until the infiltration from the wetted surface balances the emitter discharge. This results in the formation of a circle of saturated soil of infinitesimal thickness around the emitter. Thus mathematically, under trickle irrigation, three-dimensional unsaturated flow takes place from a saturated disc located on the soil surface.

Fertigation, the application of fertilizers through irrigation water, is gaining widespread popularity as an efficient way of supplying soluble plant nutrients to both irrigated orchard and field crops (Clothier, 1984). Fertilizer applications through irrigation systems are used to decrease labour costs. Limiting excessive vertical movement of the fertilizer is necessary to prevent pollution of groundwater. It is of immediate practical concern to ensure that the nutrients applied with the irrigation water are available to a substantial fraction of the root system. Understanding the simultaneous water and solute transport in two or three dimensions away from a surface line or point source is required to develop efficient strategies of fertigation.

1.1.2 Theory of the movement of nutrients

Principles

The basic principles of modeling soil water flow for trickle irrigation systems are the same as for other irrigation methods. The differences which exist are primarily in the geometry of the sources and frequency of water application (Bucks, Nakayama & Warrick, 1982). Pertinent flow occurs only in the vertical direction for sprinkler or flood systems with negligible horizontal water content gradients. On the other hand, only a small part of the total soil surface is wetted by trickle applications and the flow patterns vary vertically as well as laterally. Furthermore, trickle irrigation frequency is sufficiently high that the soil water holding capacity is of less importance than for flood or sprinkler irrigation systems.

Water moves in soils as a result of the total soil water potential ψ_T, where

$$\psi_T = h - z + \pi \qquad (1.1)$$

with h the pressure head (cm), z the soil depth (cm), and π the osmotic head (cm) (Bucks *et al.*, 1982). Each term represents energy per unit weight. Other factors are of minor importance. The pressure head h will, for the most part, be negative (i.e., the water is under a tension in the unsaturated zone), although there may be a small positive pressure in the saturated zone near the emitter or near a shallow water table. The value of h in an unsaturated soil is the soil matric potential which is equal to the absolute pressure of the water minus the atmospheric pressure (Bucks *et al.*, 1982).

The flow is describe by Darcy's law :

$$J = -K(h)\nabla\psi_T \qquad (1.2)$$

with J the water flux density (cm h^{-1}), K(h) hydraulic conductivity (cm h^{-1}) and $\nabla\psi_T$ the vector gradient of the total water potential. For unsaturated conditions, K(h) is depended upon the water status and it is a function of pressure head h. Combining Darcy's law and assuming a continuity of mass gives the Richards' equation :

$$\partial\theta/\partial t = \nabla \cdot [K(h)\nabla\psi_T] - S \tag{1.3}$$

where S is the depletion rate of water by plant roots (h^{-1}). If the osmotic potential is assumed negligible, the substitution of Equation 1.1 into Equation 1.3 gives :

$$\partial\theta/\partial t = \nabla \cdot [K(h)\nabla h] - \partial K/\partial z - S \tag{1.4}$$

Thus, mathematical modeling of the soil water flow regimes for trickle systems reduces to the solution of Equation 1.4, and is subjected to the availability of appropriate input and geometric factors (Bucks *et al.*, 1982). The solution is difficult, because of non-linearity. Also, the two- and three- dimensional wetting front geometries below trickle emitters are more complex than the one-dimensional cases, typical for many other soil water regimes. In order to solve Equation 1.4 the following inputs are required: i) the hydraulic properties of the soil, ii) the boundary conditions, iii) the initial conditions, and iv) the plant root uptake pattern.

We generally seek outputs in the form of water contents or pressure heads, the advance of wetting fronts and the direction of streamlines to be able to calculate design criteria such as emitter spacing and discharge rate. Steady state conditions rarely develop in irrigated fields (Coelho & Or, 1997). Warrick (1974) offered a more suitable analytical solution for both design and management with his transient solution of flow equations.

While considerable information can be obtained from numerical or analytical models describing water flow from point or line sources, a more complete picture of the soil water dynamics in cropped fields requires that plant water extraction patterns should be taken into account (Or & Coelho, 1996).

According to Bar-Yosef (1999), simulated and empirical results of water content distribution in soils under trickle irrigation will emphasize two practical characteristics of micro-irrigation : (i) When a dry soil is irrigated, the localized wetted soil volume has a distinct wetting front that sharply separates the wet and dry soil domains. (ii) A major fraction of the wetted soil volume has a relatively uniform water content. With these attributes we can make two important assumptions in fertigation management: (i) The wetting front position defines the boundary of the plant's soil root volume. (ii) The mean water content (θ) and nutrient concentrations (C) in the soil root volume are reasonable approximations of the actual of θ and C in the root zone (Bar-Yosef, 1999). If we accept these assumptions, the radius R (cm) of the wetting front can be determined from the soil hydraulic properties, the emitter's discharge rate, q (ml h^{-1}), and the duration of infiltration, t (h). A simple estimation under conditions of no evaporation and no water extraction is given by Equation 1.5 (Ben Asher, Charach & Zemel, 1986 as cited by Bar-Yosef, 1999):

$$R(t) = (3q\, t/\, \theta_{fc})^{1/3} \tag{1.5}$$

Two-dimensional water and solute movement in a vertical cross-section of a saturated, rigid, isotropic porous medium can be described by modified forms of the Richards' and Advection-Dispersion Equations (ADE). Richards' equation in a 2-dimensional form can be expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(h)\left(\frac{\partial h}{\partial z}+1\right)\right) - S \tag{1.6}$$

where $\theta[L^3\, L^{-3}]$ is the volumetric water content, h [L] is the pressure head, t [T] is time, x [L] is the horizontal coordinate, z [L] is the vertical coordinate taken as positive upwards, S $[T^{-1}]$ is a source/sink term representing the volume of water added by rainfall or irrigation or removed by root uptake per unit time per unit volume of soil, and K $[L\ T^{-1}]$ is the unsaturated hydraulic conductivity (Bristow *et al.*, 2000). Solution of Equation 1.6 requires that the initial distribution of the pressure head within the flow domain, the flow conditions at the boundaries of the flow region, and the soil properties are all specified. The soil properties needed are the highly nonlinear water retention $\theta(h)$ and hydraulic conductivity $K(h)$ functions, defined by using the formulations of Van Genuchten (1980).

The ADE can be expressed in the 2-dimensional form as :

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x}\left(D\,\theta\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(D\,\theta\frac{\partial C}{\partial z}\right) - \frac{\partial(q_x C)}{\partial x} - \frac{\partial(q_z C)}{\partial z} \tag{1.7}$$

where C [M L^{-3}] is solute concentration in the soil water, q_x and q_z [L T^{-1}] are the horizontal and vertical components of the volumetric flux density, D [L^2 T^{-1}] is the dispersion coefficient, assumed to obey the functional relationship

$$D = \lambda\ D_o + \varepsilon\ \nu^n \tag{1.8}$$

where λ is the tortuosity factor, D_o [L^2 T^{-1}] is the molecular diffusion coefficient of the solute in free water, ε [L^{2-n} T^{n-1}] is the dispersivity, ν [L T^{-1}] is the pore water velocity ($\nu = q\ /\ \theta$, where q = flux [L T^{-1}]), and n is an empirical constant, taken as one in the simulations by Bristow *et al.* (2000). Solution of Equation 1.7 requires knowledge of the initial concentration of a solute within the flow region as well as the solute transport properties given by Equation 1.8.

1.1.3 Factors affecting the wetting pattern

The design and operation of trickle systems should integrate plant, soil and irrigation system parameters. Warrick (1986) and Bianchi, Burt & Ruehr (1985) relate the following factors for the irrigation, soil and plant systems that will affect the wetting pattern under trickle irrigation:

- Irrigation system factors (average discharge rate q and spacing between trickle emitters)

- Soil factors (infiltration, hydraulic properties K_s and inverse of the air-entry potential (α), soil water characteristics θ vs. h, stratification and soil chemical composition)
- Chemical composition of irrigation water
- Plant characteristics (average ET rate and rooting depth)

1.1.3.1 Irrigation system factors

i) Average discharge

The advance of wetting fronts were measured by Bucks *et al.* (1982), as a function of infiltration time or cumulative irrigation application on two different soils. The two soils were a Gilat loam and a Naḥal Sinai sand. The wetting fronts were defined numerically in terms of the cumulative irrigated volume, expressed in liters. Figure 1.1 shows wetting front positions for both of the soils and for two infiltration rates, 4 and 20 l h^{-1}. The numbers of each curve in Figure 1.1 represents the water applied in 4, 8, 12, or 16 liters. Obviously the sand wetted deeper, which was due to both the ability of the sand to transmit water better and the lower water holding capacity (Bucks *et al.*, 1982).

Wider wetting patterns were also observed with the higher application rate of 20 l h^{-1} on both soils. This was the consequence of a larger wetted circle on the surface (Figure 1.1b) for the higher rate. When the water spread over a larger area on the surface, the movement was not as deep at a given quantity of water. It is evident from Figure 1.1 that the more clayey soil resulted in more spreading of water on the surface and smaller wetting depths and volumes at both emitter rates.

ii) Spacing between trickle emitters

In most trickle irrigated fields, the spacing between dripper lines and between trickle emitters along the lines are fixed. This grid-like arrangement of trickle emitters and the symmetrical geometry of flow below each of the emitters create hydraulically independent flow cells that are isolated from one another by vertical streamlines at their boundaries (Or, 1995).

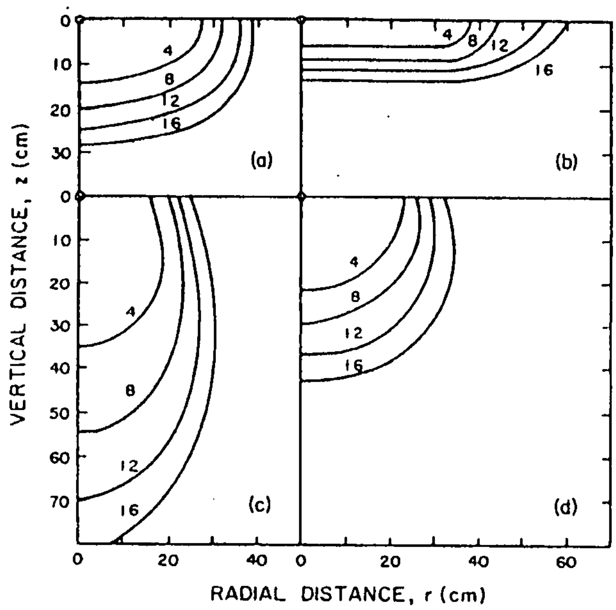


Figure 1.1 Wetting fronts as a function of infiltration time or cumulative irrigation in liters as indicated by the numbers labeled on each curve, for two soils: a) Gilat loam, q = 4 l h^{-1}; b) Gilat loam, q = 20 l h^{-1}; (c) Nahal Sinai sand, q = 4 l h^{-1}; (d) Nahal Sinai sand, q = 20 l h^{-1}; (•) single point-source emitters (Bucks *et al.*, 1982).

It is difficult to determine the minimum spacing between trickle emitters (d_{min}) for which the point source approximation remains valid. A possible approximation criterion may be based on the soil parameters K_s and α, emitter flow rate (q) and the Wooding (1968) analysis for steady flow from a shallow and circular surface pond. Adopting the notion of a saturated pond forming around an emitter, then clearly when neighboring ponds merge, an emitter line may be considered as a continuous line source. Hence, the minimum emitter spacing for the point source approximation to apply, should be larger than the pond's saturated radius (r_s) after Bresler, 1978 as cited by Or, 1995:

$$d_{min} \leq [4/(\alpha^2\pi^2) + q/(\pi K_s)]^{1/2} - 2/(\alpha\pi) \qquad (1.9)$$

Typical spacings are larger than r_s, and in many cases it is in the range of 0.5 to 1 m (Or, 1995).

1.1.3.2 Soil factors

i) Infiltration

When water is supplied to the soil surface, by precipitation or irrigation, some of the water penetrates the surface and is absorbed into the soil, while some may fail to penetrate but accumulate on the surface instead or flow over it.

The infiltration rate is defined as the volume of water flowing into the profile per unit of soil area and time. Hillel (1971) used the term infiltrability, which is the filtration flux when water at atmospheric pressure is freely available at the soil surface. This single-word replacement allows for the term infiltration rate to be used for the surface flux under any set of circumstances, whatever the rate or pressure at which the water is supplied to the soil. The infiltration rate can be expected to exceed infiltrability when the water is ponded on the soil surface with sufficient depth to exceed atmospheric pressure (Hillel, 1980).

As long as the rate of water delivery to the surface is less than the soil's infiltrability, water infiltrates as fast as it is applied and the supply rate determines the infiltration rate, the process is then supply controlled. However, once the delivery rate exceed the soil's infiltrability, it is the soil which determines the actual infiltration rate, and thus the process becomes surface or profile controlled.

In trickle irrigation, emitters apply water at a point on the soil surface. But as the infiltration does not take place at a single point of infinitesimal dimensions, water moves across the soil surface away from the emitter until the infiltration from the wetted surface equals the emitter discharge. This results in the formation of a saturated circle of infinitesimal thickness around the emitter (Figure 1.2(b)). Thus mathematically, under trickle irrigation, three-dimensional unsaturated flow takes place from a saturated disc at the soil surface. The size of the saturated area will be the largest for soils with a low infiltrability and high emitter discharge rates and it will be smallest for high intake soils and low application rates (Bucks *et al.*, 1982). When water is ponding on the soil surface to create larger circles from which water infiltrates, it will effect the wetting compared with point source emitters. Two typical flow geometries are illustrated in Figure 1.2.

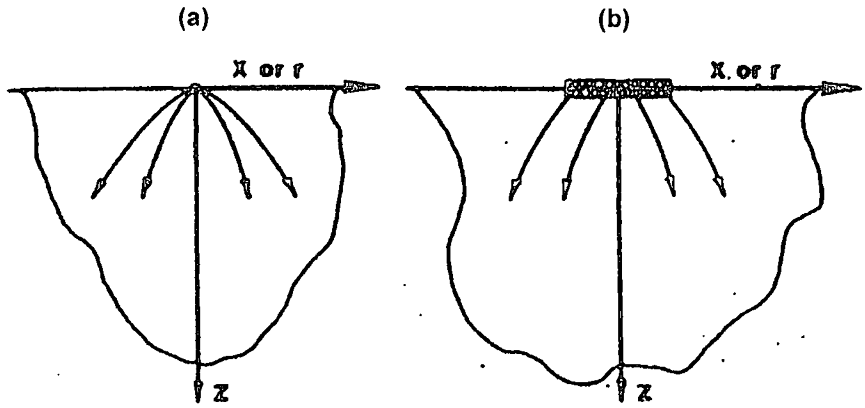


Figure 1.2 Two types of flow geometries for trickle irrigation systems: (a) point- or line- source emitters; (b) disc- or strip-source emitters (Bucks *et al.*, 1982).

The flow regime is 2 or 3-dimentional rather than only vertical (Figure 1.2(a)). The multidimensional nature of flow from point or line sources leads to more complex mathematics if the system is to be modeled.

ii) Hydraulic properties K_s and α

The relevant soil hydraulic properties are the saturated hydraulic conductivity (K_s, L T^{-1}) and α which is the slope of dln[K(h)]/dh or the rate of reduction in hydraulic conductivity with h (Or, 1995), as illustrated in Figure 1.3.

A trickle irrigated field is according to Or (1995) consist of homogeneous flow cells (emanating from the trickle emitters) each with its own soil hydraulic properties (K_s and α). The sketch in Figure 1.4 depicts a single flow cell and a view of the spatial distribution of various wetting patterns as affected by the spatial variations in soil properties. The spatial soil variability is defined through the spatial variability of the parameters α and $Y = \ln(K_s)$ (Or, 1995). These parameters are expressed as random space

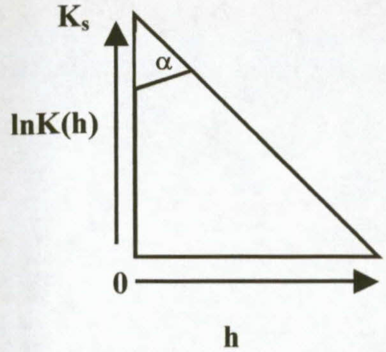


Figure 1.3 Reduction in the hydraulic conductivity with a decrease in matric potential (or increase in matric suction) will be equal to α.

functions, each comprising of an expected value and a random fluctuation:

$$\alpha = m_\alpha + \alpha' \quad \langle\alpha\rangle = m_\alpha \quad \langle\alpha'\rangle = 0 \tag{1.10}$$

$$Y = m_y + Y' \quad \langle Y\rangle = m_y \quad \langle Y'\rangle = 0 \tag{1.11}$$

where angle brackets denote the expected value operator.

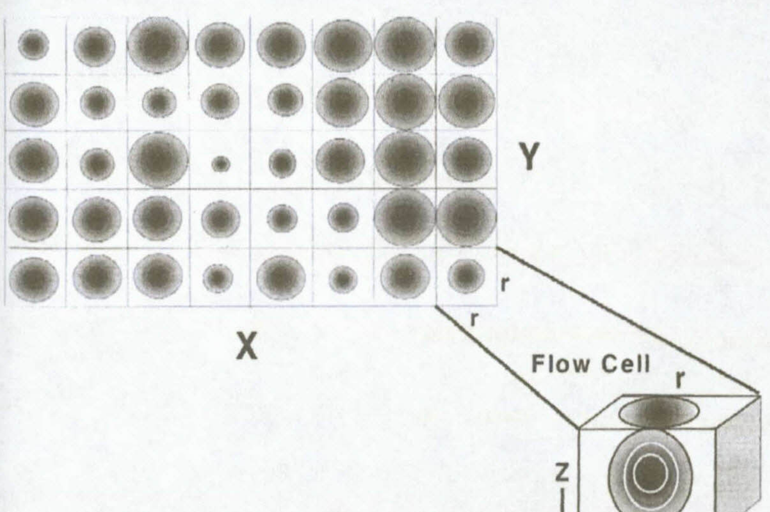


Figure 1.4 A definition sketch for the field-scale (x-y coordinates) lateral distribution of flow cells with different wetting patterns and a single flow cell (Or, 1995).

iii) Soil water characteristics θ vs. h

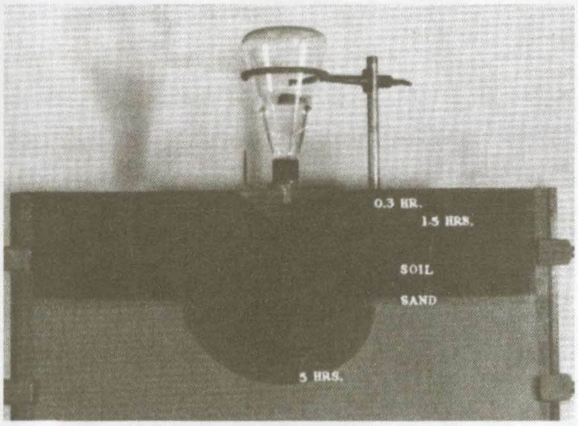
Estimation of the soil water content (θ) distribution below a point source requires a retention curve describing the relationship between h and θ (Or, 1995). Water retention curves, also called water release curves, are determined by measuring volumetric water content (θ_v) and h simultaneously, mostly in the laboratory. Relationships of h vs θ_v can be influenced by hysteresis. This is a complex process, because the deeper part of the profile, ahead of the wetting front, will normally be wetter and will follow a wetting curve while the upper part of the profile near the surface will drain following a drying curve (Gardner, Gardner & Jury, 1991). This hysteresis effect complicates matters because θ_v tends to be higher at a given h during drainage than while wetting. Thus, hysteresis can have an effect on the overall shape and dynamic behavior of the water content profile.

iv) Stratification

Soils are frequently stratified near the surface, containing layers with markedly different water retention and water conducting properties. The mathematical description of water transport through an unsaturated layered soil is very complex because of subtle effects that can occur at the interface between layers.

Even though steep hydraulic head gradients are often present, flow through a series of layers of unsaturated soil can be nearly zero under conditions where large and nearly empty pores with low hydraulic conductivities are encountered. Such conditions occur where a wetting front moving through homogeneous soil reaches a layer of coarse sand or gravel. The hydraulic head of the soil just above the wetting front may be in the order of −100 cm of water and that in the dry sand below the front may be as low as -10^3 or -10^4 cm. Despite the large gradient at the interface, the flow can drop to zero as the front reaches the coarse sand layer because there is very little water in fine pores of the sand, and the large pores cannot fill at the low matric potentials present in the upper region (Gardner *et al.*, 1991). This is illustrated in Figure 1.5(a) where a layer of coarse sand in a silt loam soil restricts downward penetration of water.

(a) (b)



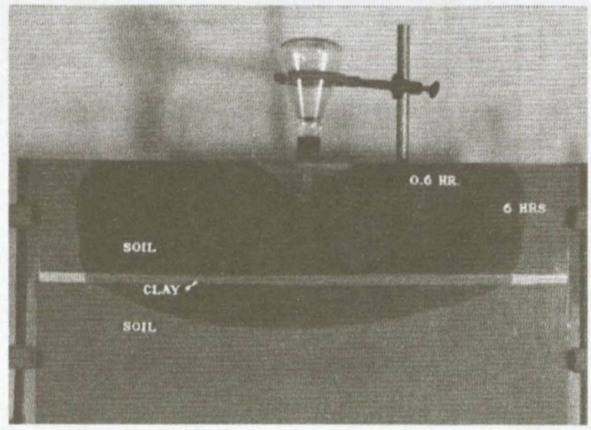


Figure 1.5 Water retention in a soil above a sand and above a clay layer (Gardner *et al.*, 1991).

Fine pores in hard and clay pans can also seriously restrict downward flow. Such materials wet rapidly when making contact with the wetting front because of the high absorptive capacity of fine pores. However, as the wetted distance over which water must move through fine pores increases, the rate of flow will decrease. Flow through such materials is often so slow that perched water tables build up above them. Rapid initial wetting followed by restriction of cross flow is illustrated in Figure 1.5(b).

(v) Soil chemical composition

Many physical soil properties can be modeled as an interaction between the diffuse double layers (DDL) of soil clay particles. The degree and nature of interaction is determined by the effective thickness of the DDL, which can be estimated with the K parameter in units of cm^{-1}.

$$K = ((8\pi e^2 z^2 n^0)/(D \cdot k \cdot T))^{1/2} \quad (1.12)$$

where e = the electron charge (coulomb/ion); z = the valence of the counter ion, n^0 is the electrolyte concentration in the bulk solution (ion/cm^3); D = the dielectric constant (coulomb/K/ion); k = the Boltzman's constant (V coulomb/K/ion); and T = absolute temperature (°K). The effective thickness of the DDL is 1/K, which have units of cm (Jurinak, 1990). If the soil solution has a high electrolyte concentration and low sodium content, infiltration will be improved due to a decrease in DDL thickness. However, when the soil solution has a high sodium content, then swelling and deflocculation of clays may occur, thus resulting in aggregate dispersion. These changes, together with translocation of dispersed clay, may lead to reduced macro porosity and permeability.

Compression of the DDL is promoted by; 1) increasing the valence of the counter ion; 2) increasing the concentration of the bulk solution; or 3) reducing the dielectric constant of the medium (Jurinak, 1990).

1.1.3.3 Chemical composition of irrigation water

It has been shown that the use of ammonium and potassium fertilizers with high quality irrigation water caused soil permeability problems. Commonly, the use of high rates of ammonium per unit of soil area with high quality, low electrolyte irrigation water and minimal disturbance of the soil surface by cultivation, decrease the permeability of the soil as the irrigation season progresses because of clay dispersion (Bianchi *et al.*, 1985). The decrease in soil permeability was due to the displacement of calcium ions on the exchange complex of the soil by monovalent ions such as ammonium and potassium. The most obvious answer to calcium loss from the soil is to provide a continuous source of calcium, which will counterbalance its removal through fertilizer use and irrigation. A readily soluble calcium source is needed. Calcium nitrate is readily soluble, but is an expensive form of calcium, and continuous application through the irrigation season would result in crop damage from excess nitrogen. Calcium chloride is an alternative but the level of chloride in the soil could be critical for some sensitive crops (Bianchi *et al.*, 1985).

Another permeability problem associated with trickle irrigation is the formation of an algal or fungal mat on the surface in the wetted area around the emitters. This is composed of fine soil particles held together by algae or fungi (Bianchi *et al.*, 1985). The high visibility of the algal-fungal mat below the emitters in affected fields led to the practice of injecting copper sulfate through the irrigation system for control. Decrease in soil pH due to the removal of calcium and application of ammonium fertilizers will result in greater mobility and availability of copper in the soil solution, with a possibility of toxicity problems for the crop.

1.1.3.4 Plant characteristics

The effective rooting depth of the cultivated crop will determine the depth over which water depletion should be calculated.

1.1.4 Fertigation

1.1.4.1 Mobility of nutrients in the soil

Fertigation is the practice where dissolved water-soluble fertilizers, liquid fertilizers or a combination of the two are applied to the crop through the irrigation system. It is important that the applied nutrients be available for uptake by plant roots and will be determined by various factors relating to the nutrients, soil, irrigation system and fertigation practices.

i) Nitrogen fertilizers

Many sources of nitrogen are suitable for injection through trickle irrigation systems. This include various nitrogen solutions, ammonium nitrate, calcium nitrate and potassium nitrate (Granberry, Harrison & Kelley, 1996). Urea is often used as a N-fertilizer. Hydrolysis of urea rapidly produces ammonium, from which oxidation generates nitrate. Urea increase soil pH upon hydrolysis and its application to soil in combination with superphosphate is undesirable (Bar-Yosef, 1999).

The two ionic forms of N found in soil are the anion NO_3^-, and the cation NH_4^+. These two ions will travel quite differently through negatively charged soils. Different sources of N fertilizers have different effects on irrigation water and soil pH (Bar-Yosef, 1999). Alkaline pH of the irrigation water is undesirable, because Ca and Mg carbonate and extractable *o*-Phosphate may precipitate in the tubes and trickle emitters. High soil pH also reduces Zn, Fe and P availability to plants. Consequently, ammonia (fertilizer solution pH >9) used in fertigation is not recommended, since it raises the pH when injected into the irrigation water.

ii) Potassium fertilizers

Potassium nitrate, potassium phosphate and potassium chloride are suitable for injection through trickle irrigation systems (Granberry *et al.*, 1996). The mechanism controlling K transport in soil is based on its rapid exchange with other cations in the soil. When the quantity of K^+ in the soil is small relative to the soil cation-exchange capacity, adsorption is controlled mainly by variations in the K^+-concentration of the soil solution (c_K). As c_K increases around a point source, the K^+ buffering capacity decreases and deeper K^+ movement is expected relative to sprinkler irrigation and broadcast K^+ application (Bar-Yosef, 1999).

Bar-Yosef (1999) has shown that at the time of maximum K^+ uptake rate by crops with a high demand for K^+, this element should be supplied through the water even when the concentration in the soil is sufficient. The release rate of sorbed K^+ into the soil solution can be to slow under trickle irrigation, where plant root volumes are restricted.

iii) Phosphorus and other fertilizers

Application of inorganic phosphorus and sulfur through trickle irrigation is not always recommended. Phosphorus and sulfur react with calcium and/or magnesium in the irrigation water to form mineral precipitates that can clog emitters (Granberry *et al.*, 1996). Phosphorus immobilization near the emitter has also discouraged its use in cropping systems where plant roots may be far from the emitters. On the other hand, Rauschkolb, Rolston, Miller, Carlton, & Burau, (1979) showed that P trickle fertigation resulted in higher P contents in tomato plants than band placing at the same P rate.

The use of sodium-based fertilizers (e.g., $NaNO_3$ or NaH_2PO_4) are unacceptable sources because of the adverse effect of Na on soil hydraulic conductivity and plant functioning (Bar-Yosef, 1999).

iv) Micronutrients

The application of micronutrients as hydroxides cause problems due to its low solubility. To avoid precipitation at pH > 5 and to facilitate sufficient transport toward roots in soil, microelements are added in solution as chelates of organic ligands. Chelates are sufficient stable to avoid displacement by other cations and to prevent precipitation or adsorption by soils and growth substrates, differing in chemical characteristics. The main chelating agents used in fertigation systems are EDTA, DTPA and EDDHA (Bar-Yosef, 1999).

1.1.4.2 Water quality and fertilizers

According to the U.S. Salinity Laboratory (1954), irrigation water with an EC exceeding 1.44 and 2.88 dS/m constitutes a moderate and a high salinization hazard, respectively. Assuming a daily irrigation of 5 mm, nitrogen and potassium concentrations in the irrigation water at the time of maximum demand may reach values of 15-20 mmol(+)/liter, which correspond to an EC of 1.5-2.0 dS/m. Under such conditions, and especially with irrigation water with an EC > 1, which is common in arid zones, care should be taken to minimize the amount accompanying ions added with the N or K. For example, KCl, which is a cheap source of K, should be replaced with KNO_3 and K_2HPO_4, while NH_4NO_3 and urea should be preferred over $(NH_4)_2SO_4$. Chloride salinity is considered more toxic for the growth of most plants then the same osmotic concentrations of SO_4^{2-}.

1.1.4.3 Solubility of fertilizer formulations

Solubility indicates the relative degree to which a substance dissolves in water. Solubility of fertilizers are a critical factor when preparing stock solutions for fertigation, especially when preparing fertilizer solutions from dry fertilizers. As indicated in Table 1.1, fertilizer formulations vary considerably in their ability to dissolve in water.

Table 1.1 Solubility of selected fertilizers in pure water (Granberry *et al.*, 1996)

Fertilizer Formulation	Solubility (kg l^{-1})
Ammonium nitrate	1.18
Calcium nitrate	1.02
Potassium chloride	0.28
Potassium nitrate	0.13

Preparation of nutrient stock solutions from dry fertilizers may require considerable time and effort and can generate sediments and scums as waste products. Therefore, commercially prepared clear liquid fertilizer solutions that are completely water soluble are often used. Liquid fertilizers are available in a variety of mixtures and can be purchased with or without micronutrients. A liquid formulation of calcium nitrate (9% N, 11% Ca) is also available. Liquid formulations such as these are very convenient, because they can be directly injected into the irrigation water.

Although transportation costs make liquid formulations a little more expensive, they save time and labour and help prevent problems associated with poorly prepared home mixes. They also eliminate the problems caused by insoluble materials found in some dry fertilizers. Even with liquid formulations, care must be taken when injecting fertilizers containing phosphorus or sulfur into trickle systems (Granberry *et al.*, 1996).

1.1.4.4 Factors affecting the distribution pattern of nutrients applied by fertigation

Soil texture, soil structure, soil hydraulic properties, soil layering, trickle discharge rate, irrigation frequency, and timing of nutrient application affects the wetting patterns and solute distribution under trickle irrigation systems. Many of these factors have already been discussed with the movement of water. The effect of soil structure and timing of nutrient application will be discussed in this section.

i) Soil structure

Soil structure can create preferential flow channels for water and dissolved solutes, which can greatly influence the characteristics of the transport process. Figure 1.6 shows breakthrough curves for chloride pulses leached through 1-m-long columns containing undisturbed and repacked loamy sand soil irrigated at a steady rate of 8 cm day^{-1}.

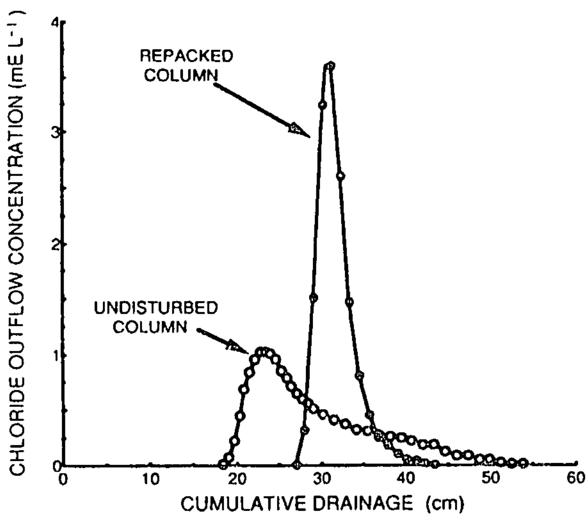


Figure 1.6 Outflow concentration versus drainage volume for long, wide, undisturbed (dashed line) and repacked (solid line) soil columns at 8 cm day^{-1} application rate and L = 94 cm (Khan, 1988 as cited by Gardner *et al.*, 1991).

Several obvious differences between the two breakthrough curves in Figure 1.6 can be observed. Less drainage was required in the undisturbed column than in the repacked column for the chloride peak to appear at the bottom. In the repacked column the chloride pulse passed completely through the system while chloride was still leaving the undisturbed column. Thus, soil structure created more dispersion or pulse spreading than in the repacked soil (Gardner *et al.*, 1991).

The continuous release of solute in the structured soil compared to the repacked soil, can be attributed to an initial diffusion of solute from the flow channels into stagnant regions of the soil. As further less concentrated solution pass through the column, there is a gradual release of the solution to the flow channels by diffusion (Gardner *et al.*, 1991).

ii) Timing of nutrient application

Recent studies have made it clear that the fate of agricultural chemicals in field soils depend greatly on the imposed boundary conditions. For example, Kluitenberg & Horton (1990), in a series of column experiments, showed that the shape of the breakthrough curve depended on how the chemical was applied to the soil. A pulse application of tracer under ponded conditions yielded faster and more pronounced breakthrough curves in undisturbed soil cores than when the tracer was allowed to infiltrate and redistribute within the soil 15 minutes before ponding of tracer-free water. The physical interpretation of this experiment is that tracer applied under a free-water surface boundary condition is able to exploit preferential pathways better and move deeper into the soil (Jaynes & Rice, 1993).

1.1.4 Examples of nutrient distribution patterns from previous research

1.1.5.1 Case study one

Chase (1985) used liquid urea phosphate with a N:P:K ratio of 15:27.2:0 to determine if phosphorus can be applied to a vegetable crop more effectively through a sub-surface trickle system than by broadcast application. Chase (1985) found that extractable P levels near the emitter and the distance phosphorus moved from the emitter increased as application rate of P increased. At the highest application rate of 1200 kg P ha^{-1}, trickle applied P moved up to ten cm laterally and 12 cm upward and downward, remaining within the root zone of lettuce plants positioned directly over a sub-surface emitter. Samples taken 23 weeks after phosphorus application showed that high levels of residual phosphorus remained in the vicinity of the emitter (Figure 1.7) (Chase, 1985). Similar effects of soil type and P application rate on the P distribution in soil under trickle fertigation can be found in studies by Bar-Yosef & Sheikholslami (1976).

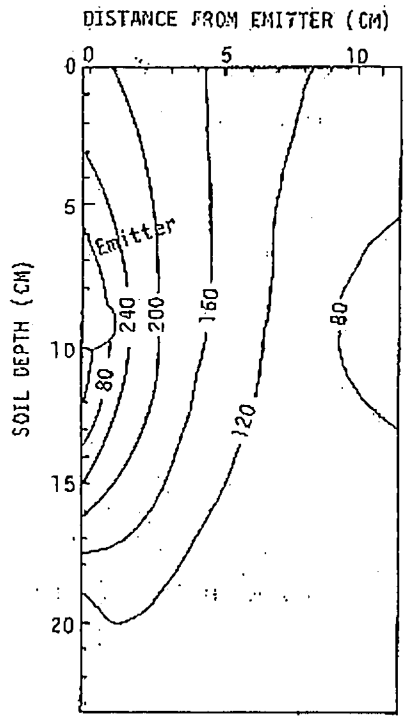


Figure 1.7 Iso-concentration lines of modified Truog extractable phosphorus in a Waimea series soil (dystrophic Hutton, Bainsvlei and Clovelley soil forms in S.A) 161 days after 1200 kg P ha^{-1} was applied through a sub-surface trickle system (Chase, 1985).

Bar-Yosef, Sagiv & Markovitch (1989) found that P trickle-fertigated sweet corn gave a significantly higher yield than trickle-irrigated sweet corn that received preplant P fertilization.

The limited migration distance of adsorbed ions with low mobility in the soil, with respect to the radius of the wetting front, implies that in many soils the distance between emitters strongly affects nutrient availability to plants. To reduce the impact of restricted mobility in soil, a combination of preplant broadcast fertilization and fertigation during the season must be practiced. The rate of preplant applications should be based on routine soil test results multiplied by a factor (<1) to account for the extra supply via the irrigation water (Bar-Yosef, 1999).

1.1.5.2 Case study two

A computer simulation study by Bristow *et al.* (2000) focussed on two different fertigation strategies to demonstrate the effect of applying nutrients under different initial conditions. In this study the HYDRUS-2D computer model (Simunek, Sejna & van Genuchten, 1999 as cited by Bristow *et al.*, 2000) was used. This model provides solutions of the Richards' and Advection-Dispersion equations to simulate two-dimensional water flow and solute movement in trickle irrigation systems with sub-surface emitters. In their simulations Bristow *et al.* (2000) applied solute with irrigation water through the circular emitter and a third-type boundary condition used to prescribe the concentration flux along the boundary of the emitter. The solute was applied as a non-reactive ion to mimic nitrate movement. They used a soil profile 1 m wide and 1 m deep and simulated water and nutrient applications to the soil through a 1 cm diameter circular emitter buried at a depth of 30 cm (Figure 1.8).

i) Soil hydraulic and solute transport properties

To demonstrate effects of different soil properties and profile features, Bristow *et al.* (2000) carried out simulations of water and solute movement with three soil types; sand, silt, and a duplex soil. The duplex soil consisted of a 30 cm upper layer of silt and a 70 cm lower layer of clay. The parameters saturated water content (θ_s), residual water content (θ_r), inverse of the air-entry potential (α), also known as the bubbling pressure, pore size distribution index (n), and saturated hydraulic conductivity (K_s) were used to define the hydraulic properties for these soils were taken from the HYDRUS-2D soils catalogue. The values are summarized in Table 1.2.

These hydraulic properties were representative of the different textural classes, and illustrated the effect that different soil properties can have on water infiltration and solute movement in trickle irrigation systems.

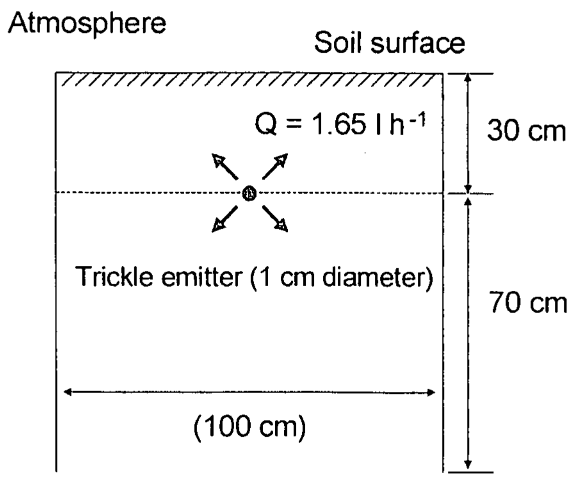


Figure 1.8 Schematic presentation showing the physical layout of the trickle irrigation system used in the simulations. Water and nutrients were applied in all directions via a 1 cm diameter emitter buried at a depth of 30 cm (Bristow *et al.*, 2000).

The solute transport properties, the molecular diffusion coefficient of the solute in free water (D_o [L^2T^{-1}]), dispersivity (ε) and macroscopic capillary length scale (λ) used in this study were based on measurements from previous studies and are also included in Table 1.2.

Table 1.2. Hydraulic and solute transport properties used for the sand, silt, and the clay layer of the duplex soil (Bristow et al., 2000)

	θ_r ($m^3\ m^{-3}$)	θ_s ($m^3\ m^{-3}$)	α (cm^{-1})	n	K_s ($cm\ h^{-1}$)	ε (cm)	$\lambda\ D_o$ ($cm^2\ h^{-1}$)
Sand	0.045	0.43	0.145	2.68	29.7	2	0.03
Silt	0.034	0.46	0.016	1.37	0.25	4	0.03
Clay	0.07	0.36	0.005	1.09	0.02	4	0.03

The K_s-value for the sand will only be expected in coarse sandy Hutton, Clovelley & Namib Soil Forms in the South African classification system. The K_s-value for the clay layer represents soils typical of the South African prisma- and pedocutanic horizons.

ii) Initial and boundary conditions

The simulations were carried out with the following boundary conditions: atmosphere at the surface of the soil profile, free drainage at the base of the profile, and zero flux of water on the sides of the flow region. Bristow *et al.* (2000) used an emitter flow rate of 1.65 l h^{-1} in all simulations, an initial pressure head of –3000 cm, and an initial solute concentration within the flow region of 0 g l^{-1}. The concentration flux along the boundary of the emitter was set equal to 4.1 g h^{-1} when applying a one-hour pulse of solute. These values where chosen to represent typical values used in trickle irrigation systems in the Australian sugar industry.

iii) Fertigation strategies

In this study they focussed on two fertigation strategies to demonstrate the effect of applying nutrients under different initial conditions (Figure 1.9).

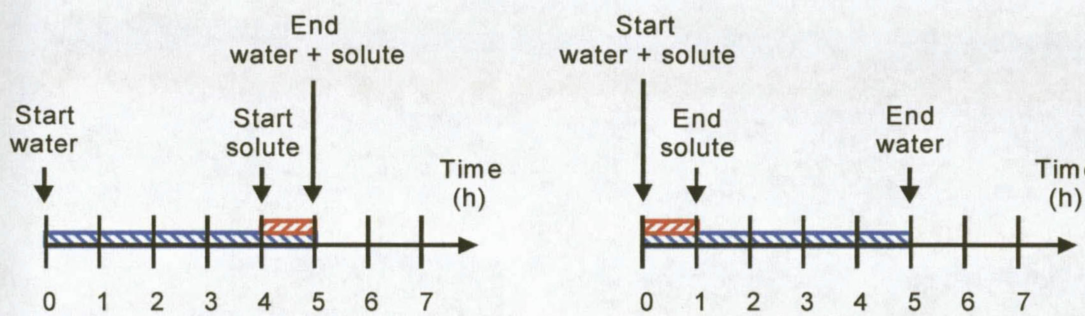


Figure 1.9 Illustrations of fertigation strategy A (solute applied at the end of the irrigation event), and strategy B (solute applied at the beginning of the irrigation event) (Bristow *et al.*, 2000).

In fertigation strategy A, water was applied via the emitter for four hours, then water and solute were applied for one hour. The total duration of the irrigation event was 5 hours, but solute was applied after the soil had been wetted for four hours by irrigation. In fertigation strategy B, water and solute were applied for one hour on a dry soil, then solute application was stopped, with water application continuing for additional four hours. The total duration of the irrigation event was 5 hours and the same amount of water and solute was applied as in strategy A. These simulations were done for a bare soil and no plant uptake.

iv) Solute movement under different fertigation strategies

Simulations of fertigation strategies A and B (Figure 1.9) were conducted for the three soils. Results for the silt and duplex soil simulations was not shown as the timing of solute application did not have much of an influence on solute transport. For both fertigation strategies, the solute stayed close to the emitter. The maximum depth below the emitter, or height above the emitter in the case of the duplex soil, and width reached by the solute was roughly 10 cm for both the silt and duplex soils.

In the sand, the timing of fertigation and initial water content strategy had a major impact on solute transport. Figure 1.10 illustrates how solute distribution evolved over time by plotting the isolines of solute concentration at 1, 2 and 4 hours after initiation of the solute pulse. Because solute was not applied at the same time for strategies A and B, the actual times at which these concentrations are plotted were not the same for strategies A and B. For strategy A, the concentration patterns were elliptical after an hour after initiation of the solute pulse, and the solute already reached a depth of 10 cm below the emitter. At 2 and 4 hours after initiation of the solute pulse, pockets of solute forming below the emitter, which continued to move downwards, can be noticed.

For strategy B, the concentration patterns were more circular than elliptical, with pockets of solute forming above the emitter (Figure 1.12). According to Bristow *et al.*(2000) these pockets of solute would be more available for plant uptake as they stayed longer near the soil surface in the root zone. Reasons for these differences in timing of ferigation and initial conditions arise because of the competition between 'capillarity' and 'gravity' to control solute movement (Bristow *et al.*, 2000). When applying solutes last via strategy A, gravity tends to dominate because solutes enter an already wet system in which downward flow occurs. When applying solutes first via strategy B, capillarity tends to dominate moving the solutes outwards and upwards from the emitter into the drier soil (Bristow *et al.*, 2000). Gravity plays a more important role as the soil becomes wetter, exerting a downward force on the 'new' water that is added, but the 'older' water with the solutes continues to move outwards and up above the emitter plane in response to capillarity. Bristow *et al.* (2000) suggested strategy B is preferable in achieving the goal of increasing water and nutrient use efficiency on sandy soils.

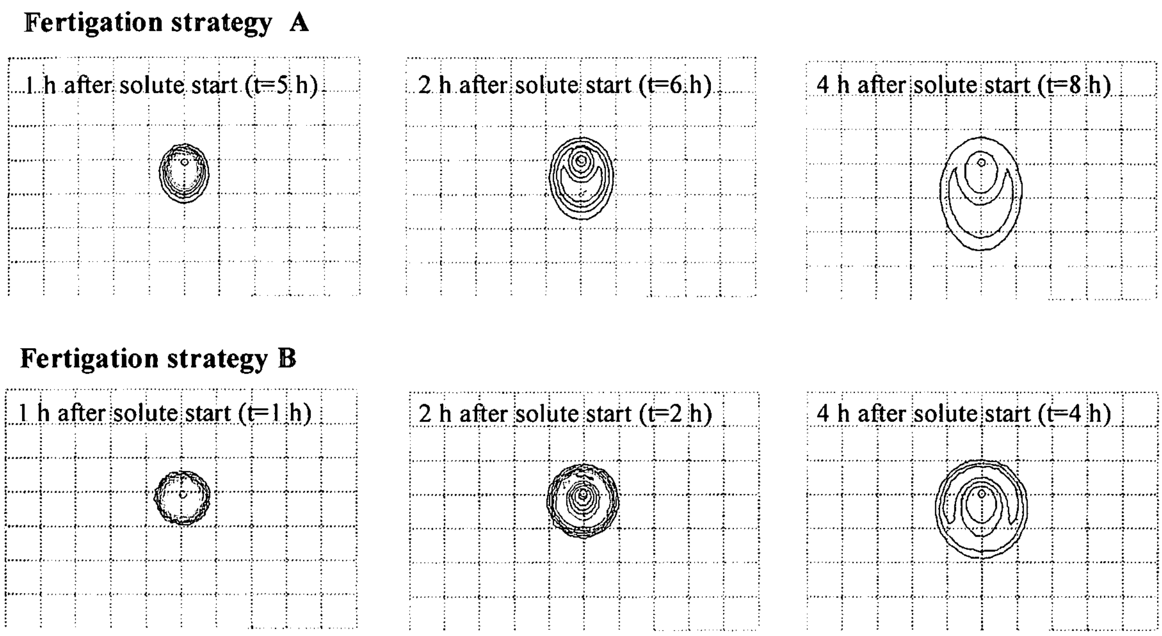


Figure 1.10 Simulation showing solute concentration around the emitter in sand irrigated using fertigation strategies A and B (Bristow *et al.*, 2000).

To quantify the differences between the two fertigation strategies, Bristow *et al.* (2000) compared solute distribution patterns in the soil profile several hours after irrigation (and fertigation) was stopped. They calculated the solute content above and below the emitter plane at t = 10 and 14 hours or 5 and 9 hours after irrigation has stopped. Figure 1.11 shows the amount of solute in the sand, in kg N ha^{-1}, at these times for both fertigation strategies.

For strategy A, at t = 10 hours, 13% of solute was above the emitter and 87% below. The pocket of solute roughly 20 cm below the emitter represented 8 kg N ha^{-1}. At t = 14 hours, 12% of solute was above the emitter and 88% below, showing that the solute continued to redistribute down the profile. The pocket of solute was then roughly 40 cm below the emitter representing 10 kg N ha^{-1}, and depending on situations such as crop growth stage, root depth, or follow up rain, could easily be leached and lost for plant uptake.

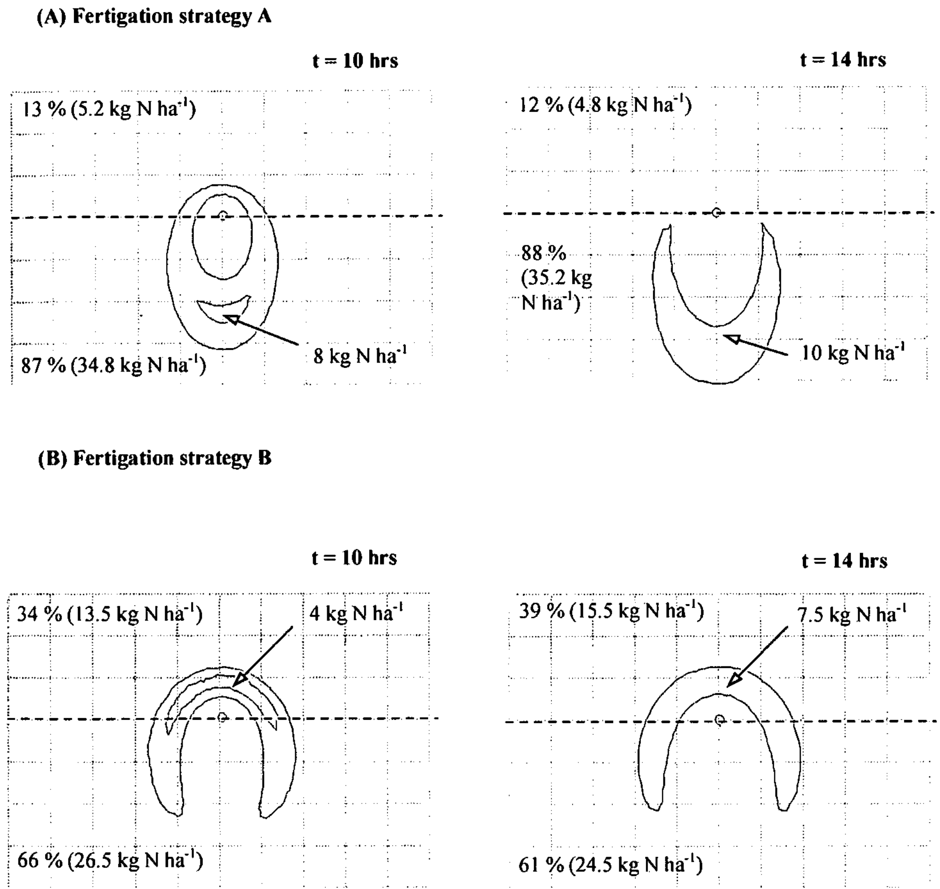


Figure 1.11 Simulation results showing the isolines of solute concentration and the amount of solute above and below the emitter at two different times for sand irrigated using (A) fertigation strategy A, and (B) fertigation strategy B (Bristow *et al.*, 2000).

These results highlight the increased risk of leaching associated with strategy A when used on highly permeable soils. In these situations most of the applied solute will move downwards below the emitter.

For strategy B, at t = 10 hours, 34% of solute was above the emitter and 66% below. In this case a pocket of solute formed above the emitter, and this pocket contained roughly 4 kg N ha^{-1}. At t = 14 hours, 39% of solute was above the emitter and 61% below, showing that the solute continued to redistribute slowly up in the profile. The pocket of solute above the emitter represented 7.5 kg N ha^{-1} and is likely to be more readily available for plant uptake than that solute that moved below the emitter.

In general more solute was held above the emitter in strategy B than in strategy A, highlighting the lower risk of leaching associated with the strategy of applying the solute in the beginning of an irrigation event and the potential for greater nutrient use efficiency with this strategy (Bristow *et al.*, 2000).

1.2 Design guidelines for South Africa

Inline emitter spacing

The criterion for inline emitter spacing in South Africa is that the diameter of the wetted area underneath the emitter should be less than 0.8 times that of the depth of the wetting area (Kleynhans, 1993). According to Kleynhans (1993) the emitter spacing on the lateral should be 80% of the wetted diameter to create a continuous wetting band. The most popular inline emitter spacings used in South Africa are 0.6 meter, 0.75 meter and 1.0 meter but other inline emitter spacing of 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.9, 1.25 and 1.5 m are also available from various manufacturers. The spacing of self-installed emitters on a polyethylene pipe is, however, not restricted to the same extent and they can be placed at any distance.

One practical method used to determine the actual distribution for a given soil type is to irrigate a given amount on the specific soil, to allow time for redistribution and then to open a profile across the row of emitters and measure directly the depth of wetting and lateral movement of the water. It is important that the adjacent wetting fronts will connect. The system will then be designed for the worst scenario using the procedure discussed above.

Lateral spacing

Lateral spacing is less critical in South Africa and the positioning of trickle lines will normally be adapted to cultivation practices. With tree crops one or two trickle lines can be used dependant on the intensity of irrigation and fertigation.

The percentage of surface area of the field that will be wetted during irrigation can be calculated as follows:

$$B_w = (80 \times l_b^2)/(l_s \times s_s) \qquad (1.13)$$

Where B_w is the partial wetting of the field (%), l_b^2 the wetting diameter under an emitter (m), l_s spacing of emitter laterals (m) and s_s the inline emitter spacing (m) (Kleynhans, 1993). According to Kleynhans (1993) better utilization of rainfall can be made when the wetted soil volume (B_w) are restricted to between 33 and 50 %.

1.3 Problem statement

The worldwide micro-irrigated area increased steadily to a total of about 1.8×10^6 ha in 1991 (Coelho & Or, 1997). As water scarcity increase, there is an ongoing need to optimize water use efficiency. The correct design of a trickle irrigation system, on a given soil type, is essential and is one way of achieving better water use efficiency. While some guidelines have been published to help growers install, maintain and operate trickle irrigation, there are at present few, if any, clear guidelines in South Africa for designing and managing trickle irrigation systems, that accommodate differences in soil hydraulic properties. Systems are often designed to an economic optimum in terms of the engineering principles, which may not produce the best environmental outcomes. There is an ongoing need for assessment and continuous improvement of practical guidelines for designing and managing irrigation/fertigation systems.

1.4 Hypothesis

Water movement is dependent on various soil factors as well as emitter discharge rates. Water distribution patterns will differ on different types of soil. Emitter discharge rate will also have an effect on the wetting pattern and water distribution on the same soil.

Timing of nutrient application is very important. Nutrients will have a different distribution pattern when applied in the beginning of an irrigation event when the soil is dry, than when applied later in the irrigation event when the soil is already wet.

1.5 Objectives

If trickle irrigation is to provide the benefits expected of it there is a clear need to make better use of soil properties and soil profile information to provide more efficient and robust irrigation and fertigation guidelines. The main objectives of this study is:

- To quantify the dimensions of the wetted volume below trickle emitters on three soil types and to extrapolate this data so it could be applied on more soil types.

- To quantify the movement of nitrate in a single soil and to determine if timing of application plays any role in its distribution.

- To evaluate the available design and management guidelines for trickle irrigation systems on soils with different hydraulic properties. The objective is to ensure water and solutes (nutrients and agrochemicals) are held within the root zone to maximize plant uptake and minimize drainage and leaching.

CHAPTER 2

Materials and Methods

2.1 Soil

Three different types of soils were used in the study:

- Non-luvic fine sand
- Luvic fine sand
- Sandy clay loam

2.1.1 Non luvic fine sand

2.1.1.1 Location

This site is situated between Bultfontein and Hoopstad, on the farm Poppieland (28°03'S,25°58'E and an elevation of 1126 m above mean sea level).

2.1.1.2 Soil properties

This non-luvic fine sandy soil is a 3 meter deep Clovelley Buckland (2100) (Soil Classification Working Group, 1991). The particle size distributions of the soil is given in Table 2.1 for the different depth intervals.

2.1.2 Luvic fine sand

2.1.2.1 Location

This site is situated 12 km Northwest of Bloemfontein, adjacent to Tempè airport on the farm Kenilworth subdivision 19 (29°01'S,26°09'E and an elevation of 1362 m above mean sea level).

2.1.2.2 Soil Properties

This luvic fine sand soil is a 3 meter deep Bainsvlei Amalia (3200) (Soil Classification Working Group, 1991). The particle size distribution of the soil is given in Table 2.2 for the different depth intervals.

Table 2.1 Particle size distribution for the non-luvic fine sandy soil for 10 cm depth intervals

Depth (cm)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Coarse Silt (%)	Fine Silt (%)	Clay (%)	Silt + Clay (%)
5	0.7	9.6	82.2	1.52	1.0	5.0	6.0
15	0.8	10.3	81.1	1.52	1.1	5.3	6.5
25	0.9	11.8	78.9	1.44	1.4	5.8	7.5
35	1.1	13.4	75.7	1.36	1.8	7.0	9.1
45	1.2	15.2	71.4	1.27	2.3	9.0	11.4
55	1.2	15.7	69.3	1.19	2.5	10.3	12.9
65	1.1	14.8	69.4	1.09	2.5	10.8	13.6
75	1.1	14.9	68.6	0.99	2.0	11.9	14.4
85	1.1	15.8	67.0	0.90	1.0	13.6	15.1
95	1.2	16.0	66.1	0.80	0.4	14.6	15.9
105	1.2	15.4	65.9	1.02	0.1	14.9	16.6
115	1.2	15.0	65.9	1.25	0.5	14.8	16.8
125	1.3	14.9	66.1	1.47	1.5	14.3	16.3
135	1.2	14.3	66.6	1.69	1.9	14.4	16.3
145	1.1	13.4	67.3	1.60	1.6	15.1	16.8
155	1.0	12.9	67.7	1.52	1.5	15.5	17.0

2.1.3 Sandy clay loam

2.1.3.1 Location

This site is situated 20 km Northwest of Bloemfontein, on the farm Vrede (28°58'S, 26°07'E).

2.1.3.2 Soil Properties

This clay is a 1.5 meter deep Valsrivier Aliwal (1122) (Soil Classification Working Group, 1991). The particle size distribution of the soil is given in Table 2.3 for the different depth intervals.

Table 2.2 Particle size distribution for the luvic fine sand soil for every 10 cm depth intervals

Depth (cm)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Coarse Silt (%)	Fine Silt (%)	Clay (%)	Silt + Clay (%)
5	0.37	5.86	81.79	1.23	3.00	7.75	11.50
15	0.34	6.27	82.16	1.37	2.38	7.50	10.50
25	0.30	6.67	82.52	1.51	1.75	7.25	9.50
35	0.24	5.33	80.36	0.00	3.00	11.75	15.50
45	0.31	5.38	74.30	2.51	2.25	15.25	17.50
55	0.24	5.18	74.13	2.08	2.25	16.13	18.38
65	0.16	4.98	73.95	1.66	2.25	17.00	19.25
75	0.17	4.86	74.58	1.02	2.38	17.00	20.00
85	0.17	4.80	74.90	0.70	2.44	17.00	20.38
95	0.17	4.74	75.21	0.38	2.50	17.00	20.75
105	0.19	4.85	74.54	1.16	2.25	17.00	20.56
115	0.20	4.91	74.21	1.56	2.13	17.00	20.47
125	0.22	4.97	73.87	1.95	2.00	17.00	20.38
135	0.24	5.08	73.20	2.74	1.75	17.00	20.19
145	0.25	5.13	72.87	3.13	1.63	17.00	20.09
155	0.26	5.19	72.53	3.52	1.50	17.00	20.00
165	0.26	5.19	72.53	3.52	1.50	17.00	20.00
175	0.55	5.28	67.56	4.36	2.00	20.25	23.75
185	0.48	5.34	65.94	3.62	2.63	22.00	26.00
195	0.41	5.40	64.32	2.87	3.25	23.75	28.25

2.2 Mobile trickle system

A mobile trickle system consisting of a 1000 *l* tank, pump with filter, power generator, dragline, 20 mm class three pipe and a fertilizer tank was designed. Emitter rates of 1.2, 2 and 8 l h^{-1} were used.

Table 2.3 Particle size distribution for the sandy clay loam soil for every 10 cm depth intervals

Depth (cm)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Coarse Silt (%)	Fine Silt (%)	Clay (%)	Silt + Clay (%)
5	0.1	1.9	69.8	1.70	4.5	22.0	26.5
15	0.1	1.9	67.2	4.84	3.3	22.8	27.5
25	0.1	2.1	64.2	5.57	3.5	24.5	29.5
35	0.2	2.2	60.0	5.73	3.4	28.6	33.5
45	0.2	2.2	55.7	5.89	3.3	32.8	37.5
55	0.1	2.2	55.4	5.98	3.2	33.1	38.1
65	0.1	2.1	55.1	6.08	3.1	33.5	38.6
75	0.1	1.9	54.5	6.26	3.0	34.3	39.8
85	0.1	2.2	53.8	6.51	3.2	34.3	39.6
95	0.1	2.4	53.1	6.75	3.4	34.3	39.4
105	0.1	2.8	51.8	7.24	3.8	34.3	39.0
115	0.2	2.9	51.8	7.03	3.6	34.4	39.6
125	0.2	3.1	51.9	6.82	3.4	34.6	40.1
135	0.3	3.3	52.0	6.40	3.0	35.0	41.3

The inline emitter spacing was 60 cm. The emitters were all pressure compensated and supplied by Netafim. The 1.2 l h^{-1} emitters were pre-installed (RAM) type and the 2 and 8 l h^{-1} emitters were buttons manually installed into 20 mm class 3 PE tubing. A picture of the mobile trickle system is shown in Plate 2.1.

2.3 Design characteristics of the mobile trickle system

Three emitter discharge rates of 1.2, 2 and 8 l h^{-1} were used as treatments. The design was based on a fixed inline emitter spacing of 60 cm and a fixed lateral spacing of 1.5 m giving 11 189 emitters per hectare (Table 2.4). The wetting patterns were determined around a single line of emitters. The actual discharge rates of the emitters as well as the volumes (liter) per emitter that should be applied to give a specific irrigation amount (mm), are given in Table 2.4.

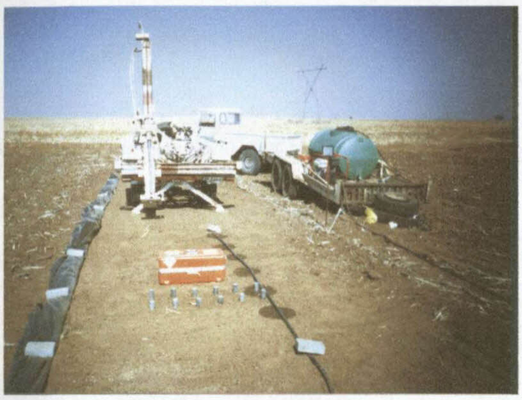


Plate 2.1 Photos of the mobile trickle system.

2.4 Irrigation events

The research was conducted in two phases. During the first phase the wetting patterns on three soil types and three emitter discharge rates were investigated. In the second phase the distribution patterns of fertigated nitrate on one soil type and an emitter discharge rate of 2 l h^{-1} was studied. Two irrigation events were used. During the first irrigation event, 50 mm water was applied on dry soil, after which 3 days was allowed for redistribution. During the second irrigation event, 20 mm water was applied on the wet soil and again 3 days was allowed for redistribution.

2.5 Water distribution measurements

The wetting front for each type of soil was measured as follows: Neutron probe access tubes were installed in a straight line perpendicular with an emitter at distances of 5, 25, 45, 65, 85, 105, 125 and 145 cm away from the emitter (Figure 2.1 and Plate 2.2). Another line of access tubes was installed between two emitters at the same distances from the line to get accurate average readings over the whole area including the overlap.

Table 2.4 The actual discharge rates of the emitters, the number of emitters per hectare as well as the volumes (liter) per emitter used

<table>
<tr><td colspan="4">Emitter discharge rates</td><td colspan="4">Water applied (liter) per emitter after</td></tr>
<tr><td colspan="2">Theoretical flow rate</td><td colspan="2">Actual flow rate</td><td>10mm</td><td>20mm</td><td>30mm</td><td>50mm</td></tr>
<tr><td>1.2 l h^{-1}</td><td>1.3 mm h^{-1} ha^{-1}</td><td>1.2 l h^{-1}</td><td>1.3 mm h^{-1} ha^{-1}</td><td>9</td><td>18</td><td>27</td><td>45</td></tr>
<tr><td>2 l h^{-1}</td><td>2.2 mm h^{-1} ha^{-1}</td><td>2.4 l h^{-1}</td><td>2.7 mm h^{-1} ha^{-1}</td><td>9</td><td>18</td><td>27</td><td>45</td></tr>
<tr><td>8 l h^{-1}</td><td>9.0 mm h^{-1} ha^{-1}</td><td>9.2 l h^{-1}</td><td>10.3 mm h^{-1} ha^{-1}</td><td>9</td><td>18</td><td>27</td><td>45</td></tr>
<tr><td colspan="8">The number of emitters per hectare</td></tr>
<tr><td colspan="4"></td><td colspan="2">Trickle emitters/1000 cm line</td><td colspan="2">Trickle emitters ha^{-1}</td></tr>
<tr><td colspan="2">Inline spacing (cm)</td><td colspan="2">60</td><td colspan="2">167</td><td colspan="2">11189</td></tr>
<tr><td colspan="2">Line spacing (cm)</td><td colspan="2">150</td><td colspan="2">67</td><td colspan="2"></td></tr>
</table>

The water content, expressed in mm water per 100 mm soil, was measured at depths of 5, 15, 25, 35, 45, 55, 65, 75 etc, till a depth of 155 cm, in each access tube with a Campbell Pacific 503 neutron probe before each irrigation event started. These readings were used as a control. After a given amount of water was applied, or following redistribution, readings were taken again at the same depths. The average value of the reading perpendicular with the emitter and between the 2 emitters was used to calculate the gains in water content at each of the depths by subtracting the control.

2.5.1 Time of measurement

For the first irrigation event of 50mm, neutron probe readings were taken after 10mm, 20mm, 30mm and 50mm water was applied. Water gained in each 5x10x10 (measurements 5 cm away from emitter) and 20x10x10 (measurements for the 25, 45, 65 85 etc. cm away from the emitter) cm cell was determined by subtracting the control from the measured water content. With this method, water movement could be expressed in a grid-like pattern with a two dimensional plane for one quadrant. The wetting patterns are given in a diagram indicating the amount of applied water in each cell as shades of blue, assuming that the opposite quadrant is symmetrical. Interpolation was used to reduce the cell sizes to 5x5x5 cm. After the 50mm irrigation on the dry soil and following 3 day redistribution, a further 20 mm irrigation was applied, again allowing 3 days for redistribution. Water content readings were compared after 20 mm and 50 mm irrigation on the dry soil, after the following 3 day redistribution, after the 20mm irrigation on the wet soil and after the following 3 day redistribution.

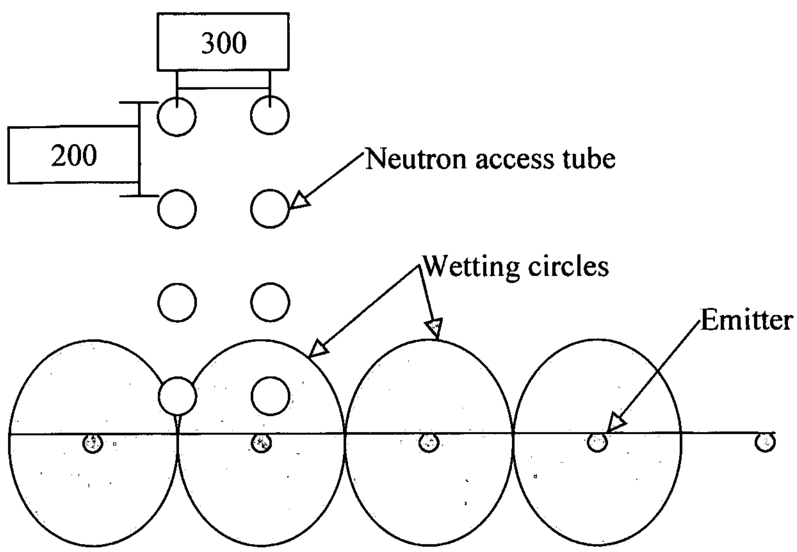


Figure 2.1 View from above to illustrate the layout of neutron access tubes.

2.6 Measurement of nitrate distribution

In the second phase of the experiments, the distribution patterns of nitrate applied through fertigation, was investigated on the luvic fine sand with an emitter discharge rate of 2 l h^{-1}. The wetting patterns were determined around a single line of emitters with design characteristics similar to the water distribution measurements. This study consisted of two experiments. During the first experiment, nitrate was applied through the emitters in the beginning of the irrigation event on a dry soil. During the second experiment, nitrate was applied at the end of the irrigation event which started on a dry soil.

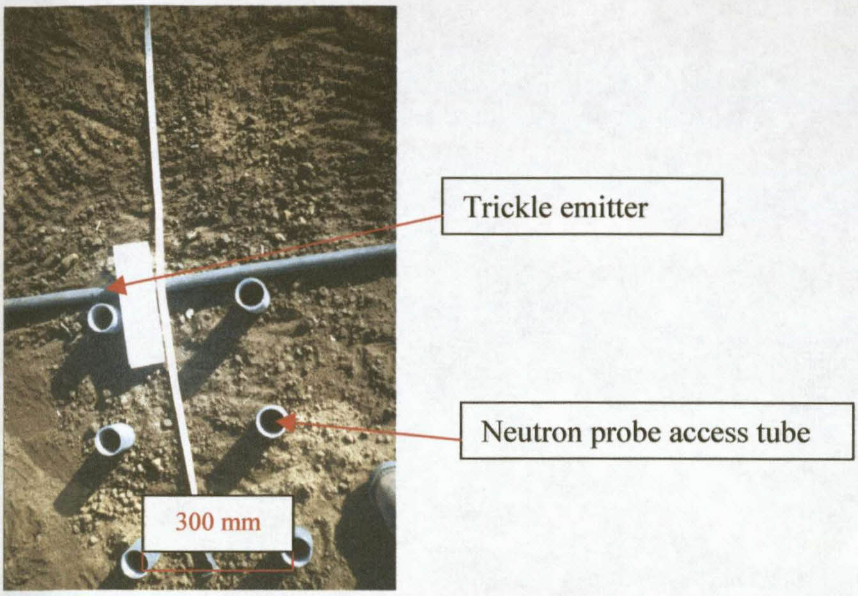


Plate 2.2 Photograph to illustrate the experimental layout.

2.6.1 Irrigation event

The irrigation event used for measuring the nitrate distribution was calculated using the computer program BEWAB which was developed in the Department of Soil Science (Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, 1988). Guidelines used were based on maize production under irrigation. With a target yield of 10 ton per hectare, a profile available water capacity during peak use of 120 mm and a rain storage capacity of 30 mm, it was determined that 460 mm irrigation should be applied over the first 90 days of the growth cycle, thus on average 5 mm per day. A 4 day irrigation cycle was selected with a total of 20 mm per application. This compared well with the procedure used in determining the water distribution patterns describe in Section 2.6.

Nitrogen was applied as calcium nitrate ($Ca(NO_3)_2.4H_2O$) which contained 11.86% N (26.25% NO_3^-), at a total application rate of 220 kg N ha^{-1} which is typical for high yielding maize production under irrigation. The fertilizer was split in 5 increments, rather than the recommended 10 increments, to create a higher nitrate concentration that could be detected more easily. Thus a single 44 kg N ha^{-1} increment was applied with 20 mm of water. The nitrate solution was prepared by dissolving 265.23 g of $Ca(NO_3)_2.4H_2O$ in 16 liter distilled H_2O tot give a concentration of 4.35 g NO_3^- l^{-1}(C_o). The solution was injected into the system by using a separate container for the nitrate solution with a 2-way valve, used to change from irrigating water to the fertilizer solution and vise versa. Water used for irrigation was purified by a tri-osmosis filter and had a nitrate concentration of less than 0.003 mg l^{-1}.

Experiment 1

During the first experiment, the nitrate was applied during the first 50 minutes (2.2 mm) of the 20 mm irrigation event (Figure 2.2). Three days was allowed for redistribution before the first samples were taken with a soil auger. Samples were taken perpendicular to and between two emitters at the same distances and depths from the emitter as for the water distribution measurements (Section 2.5). All the samples were dried, crushed and sieved through a 2 mm sieve. Nitrate was measured with the Salisilate-method (Hoffmann, 1974). The increase in nitrate content, expressed in mg kg^{-1} at each of the depths were obtained by subtracting the readings before from the readings after application. On the fourth day, another 20 mm irrigation was applied, after three days, allowing for redistribution, the last samples were taken.

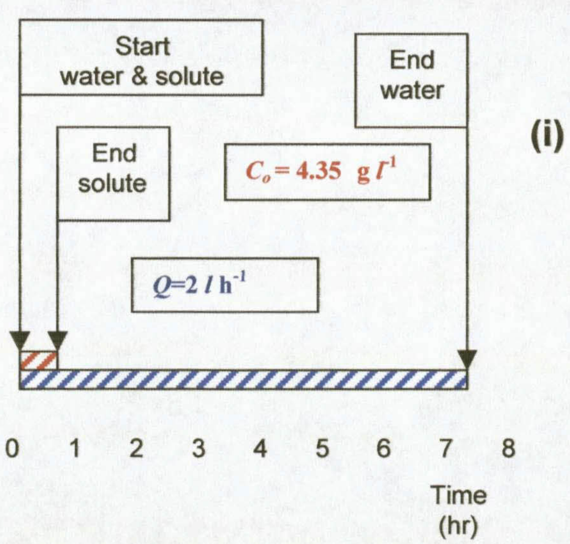


Figure 2.2 Schematic illustrations of the timing of fertigation where the NO_3^- was applied at the beginning of the irrigation event.

Experiment 2

During the second experiment, the nitrate was applied during the last 2.2 mm (50 minutes) of the irrigation event of 20 mm (Figure 2.3). Again three days was allowed for redistribution before the first samples were taken. On the forth day, another 20 mm was applied. After three days was allowed for redistribution, the last samples were taken.

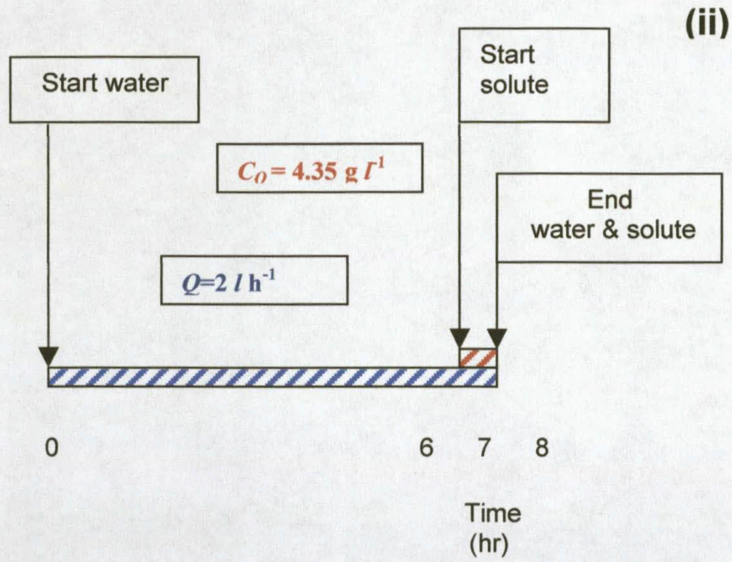


Figure 2.3 Schematic illustrations of the timing of fertigation where the NO_3^- was applied at the end of the irrigation event.

The nitrate distribution patterns will be presented in diagrams indicating the amount of fertigated nitrate in each cell as shades of blue, assuming that the opposite quadrant, which was not sampled, as symmetrical. Interpolation was used to reduce the cell sizes from 5x10x10 and 20x10x10 to 5x5x5 cm. For the nitrate distribution the line perpendicular to the emitter and the line between two emitters were used separate to give the distribution of nitrate below the emitter and between two emitters.

CHAPTER 3

The effect of texture and emitter discharge rate on wetting patterns

3.1 Introduction

Both soil texture and emitter discharge rate has an effect on the wetting pattern below trickle irrigation emitters. Soil texture is a very stable soil property and is valuable because of its inter relationship with other soil properties. Particle size distribution (texture) and soil structure affect the infiltrability, hydraulic conductivity, water retention and porosity of soils, which are all important processes determining water movement through soils.

According to Hillel (1980) soil infiltrability and its variation with time, depend upon the initial wetness and suction, as well as on the texture, structure and uniformity of the profile. In surface trickle irrigation, emitters apply water at a point on the soil surface. Because infiltration does not take place at a single point of infinitesimal dimensions, water moves across the soil surface away from the emitter until the infiltration from the wetted surface equals the emitter discharge. This results in the formation of a saturated circle of infinitesimal thickness around the emitter. Thus mathematically, under trickle irrigation, three-dimensional unsaturated flow takes place from a saturated disc at the soil surface. The size of the saturated area will be the largest for soils with a low infiltrability (clayey soils) and high emitter discharge rates and it will be smallest for high intake (sandy) soils and low emitter rates (Bucks *et al.*, 1982). When water is ponding on the soil surface to create larger circles from which water infiltrates, it will modify the wetting pattern compared with point source infiltration.

Infiltrability of soils is high in the early stages of infiltration, particularly where the soil is quite dry, but tends to decrease until it reaches a constant rate, which is often called the final infiltration capacity or steady-state infiltrability. The decrease of infiltrability result from deterioration of the soil structure and the consequent formation of a surface crust. It also decreases from swelling of the clay, reducing the macro porosity or from entrapment of air bubbles or the bulk compression of soil air where it is prevented from escaping, as it is displaced by water.

The wetter the soil, the lower will the initial infiltrability be, because of smaller suction gradients and less empty pores, and the quicker will the constant rate be attainted. Infiltrability also depends on the saturated hydraulic conductivity of the soil and will increase with an increase in saturated hydraulic conductivity (Hillel, 1980). Layers in the soil, which differ in texture and structure, may retard water movement during infiltration. Clay layers impede flow due to its lower saturated conductivity.

With trickle irrigation, a small part of the soil surface below the emitter is saturated with water. Ponding will commence when all the pores are filled with water and the application rate exceeds the downward movement of water under influence of gravitational potential. Water flows faster through macro than micro pores, because of a lower flow resistance, therefore the saturated hydraulic conductivity will increase with an increase in macro porosity. Below this saturated zone will be an unsaturated zone of uniform wetness, known as the transmission zone (Hillel, 1980).

3.2 Results and discussion

3.2.1 General

The wetting patterns for the different soils, emitter discharge rates and irrigation treatments are presented in Figures 3.1 to 3.9. The amount of water (mm) gained per 5x5x5 cm cell is indicated in shades of blue. In each figure (a) represents the wetted area after 20 mm irrigation on a dry soil, (b) the wetted area after an additional 30 mm or a total of 50 mm irrigation on a dry soil. The symbol (c) gives the wetted area three days after the 50 mm irrigation on a dry soil. The symbol (d) shows the newly wetted area immediately after 20 mm irrigation on a wet soil and (e) three days after the 20 mm irrigation on the wet soil. The symbol (f) represents the wetted area after 8 days at the end of the experiment, following an initial 50 mm irrigation on a dry soil and a further 20 mm irrigation 4 days later on the wet soil.

The most acceptable way to quantify the wetted area is with the width to depth ratio of the wetting front. It was decided to use wetting patterns (c) and (e) for this purpose. Both representing wetting patterns three days after a 50 mm irrigation on a dry soil and a 20 mm irrigation on a wet soil respectively. Wetting pattern (e) is representative of practical field situations.

3.2.2 Effect of texture on the width to depth ratio of the wetting front

3.2.2.1 Wetting pattern after redistribution following a 50 mm irrigation on dry soil

i) Non-luvic fine sand

The water distribution patterns with emitter discharge rates of 1.2, 2 and 8 l h^{-1} are presented in Figures 3.1, 3.2 and 3.3 respectively for the non-luvic fine sand. The dimensions of Figures 3.1 (c) to 3.3 (c) were used for calculation of the width : depth ratio (Table 3.1). The average width to depth ratio was 1.1 which shows that the width and depth of distribution was almost the same and water moved through the soil in a square shape distribution pattern (Figures 3.1 (c) to 3.3(c)).

During redistribution most of the water moved downward in a ball-shape to depth of 95 cm. The wetting front reached an average depth of 153 cm and moved laterally to an average width of 173 cm for the three emitter rates (Table 3.1). The wetting patterns of the 1.2 and 2 l h^{-1} emitters were almost similar but the 8 l h^{-1} emitter gave a wider wetting pattern due to some ponding on the surface. The lateral movement was measured at the widest part of the wetting front in the profile. The faster vertical advance of the wetting front, primarily because of gravity, was due to the lower water-holding capacity and the ability of sand to conduct water faster. The average silt plus clay content of the wetted volume was 13.31%.

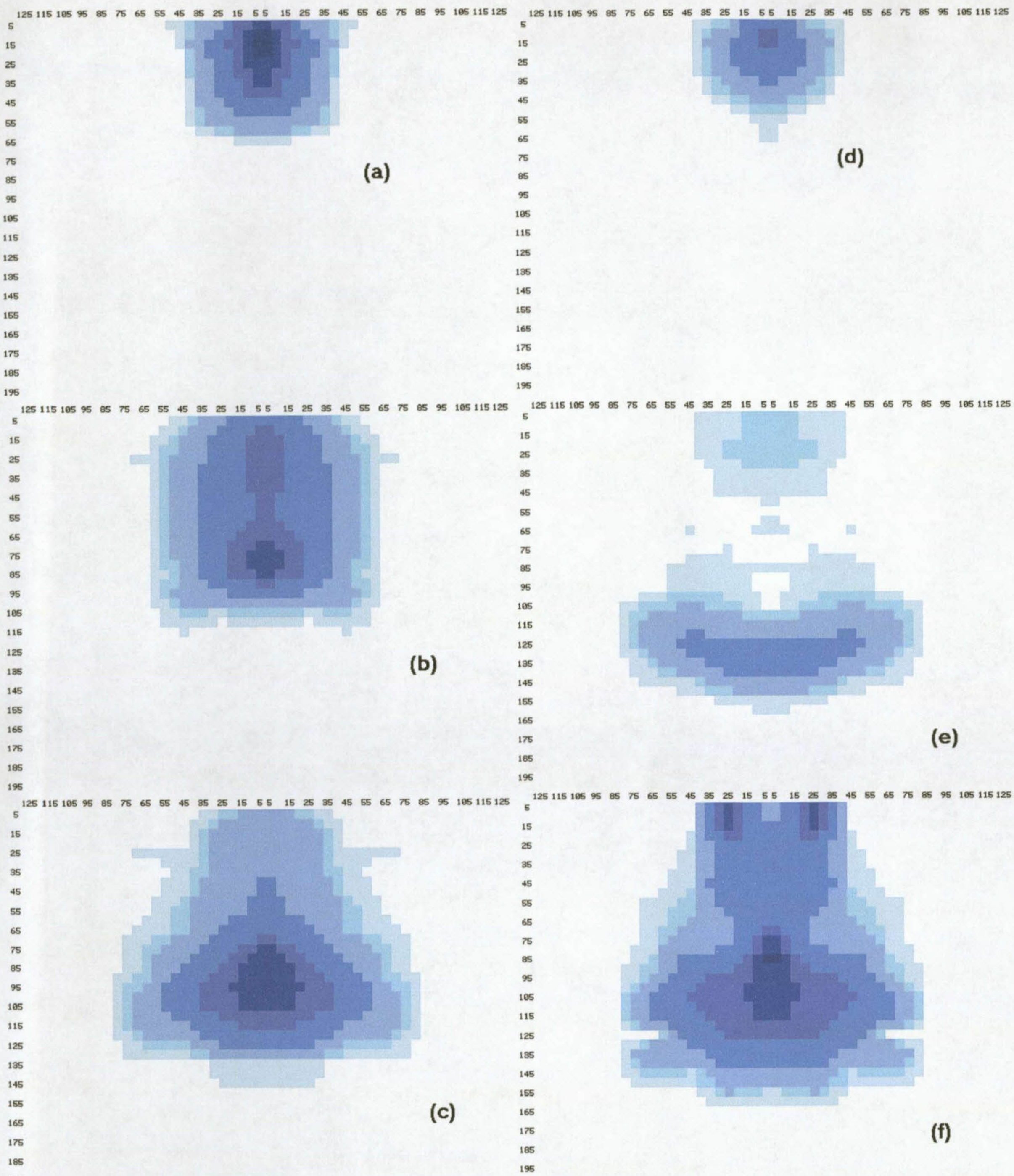
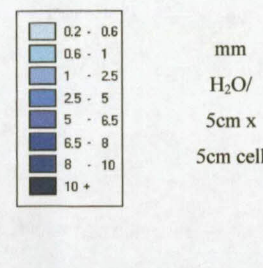


Figure 3.1 Water distribution diagrams for the non-luvic fine sand, with emitter discharge rate of 1.2 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



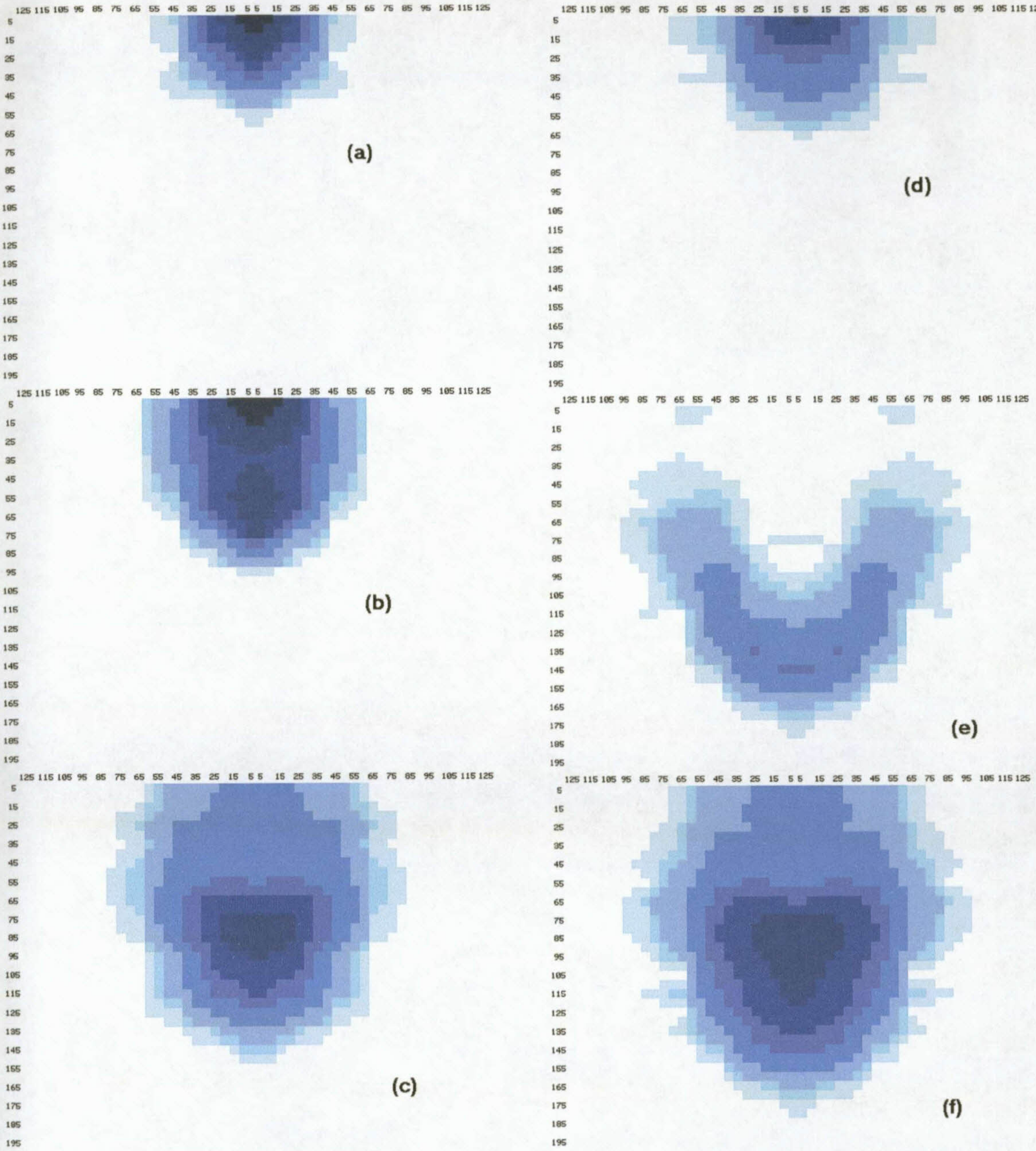
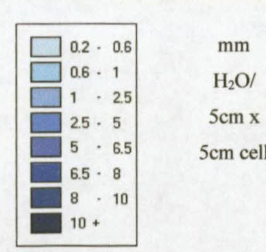


Figure 3.2 Water distribution diagrams for the non-luvic fine sand, with emitter discharge rate of 2 *l* h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



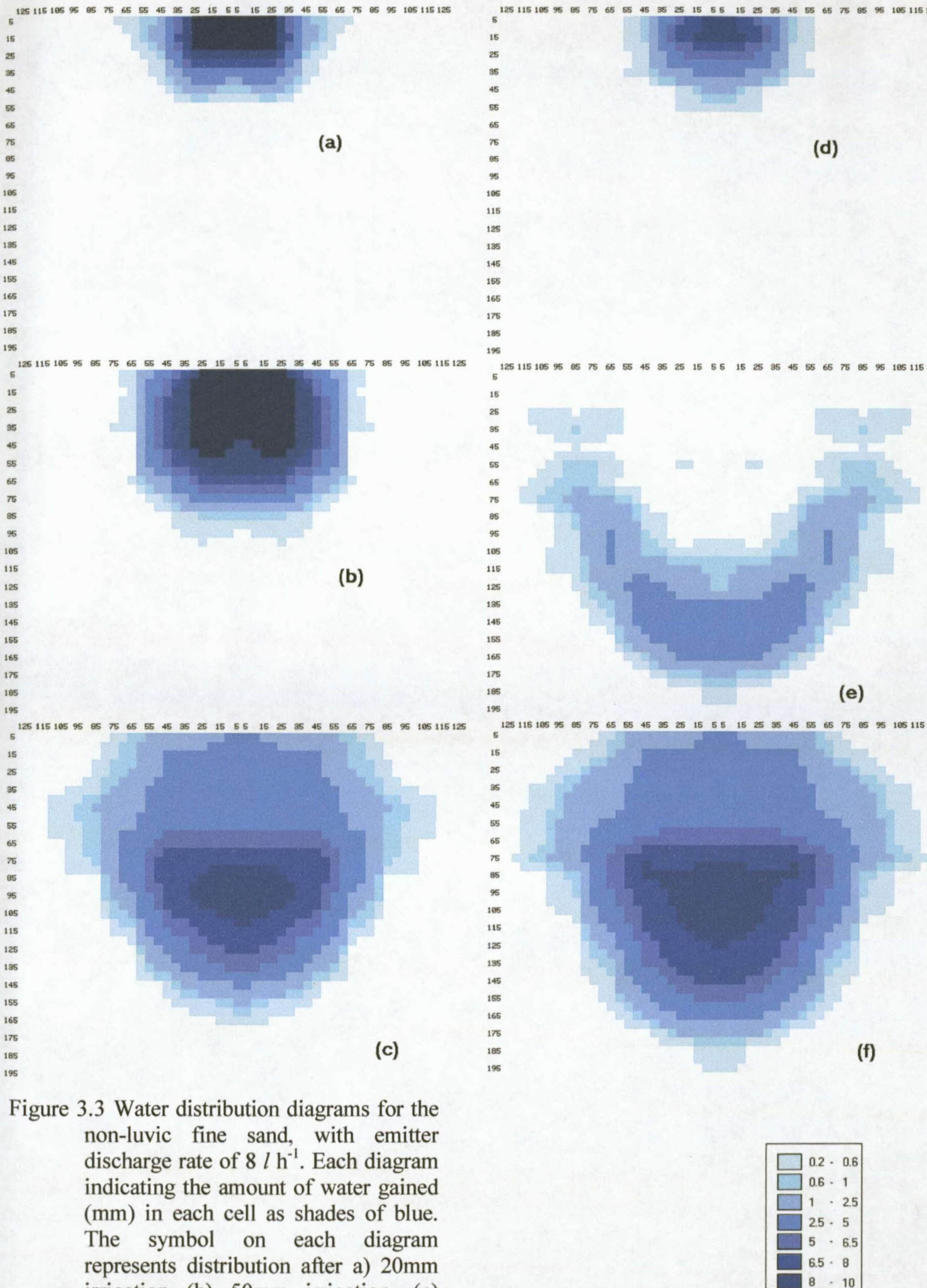
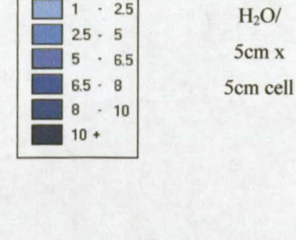


Figure 3.3 Water distribution diagrams for the non-luvic fine sand, with emitter discharge rate of 8 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



ii) Luvic fine sand

The wetting patterns of the luvic fine sand for different emitter discharge rates are illustrated in Figures 3.4 to 3.6. The wetting front dimensions are given in Table 3.1.The average width to depth ratio of 1.9 shows that the width was almost twice the depth of distribution and water moved through the soil in a rectangular distribution pattern (Figures 3.4 (c) to 3.6 (c)). The silt + clay increased from 9.5% for the 0-25 cm topsoil to 15.5% at a depth of 35 cm. This rapid change in texture comply with the criteria for a luvic soil and is the main reason why most of the water tended to stay within the top 30 cm of the profile. The more clayey layer wetted rapidly after making contact with the wetting front because of the high sorptive capacity of fine pores. However, as the wetted distance over which water must travel through fine pores increased, the rate of flow decreased (Gardner *et al.*, 1991). The slower flow through the subsoil layer resulted in a more saturated zone developing above them (Figures 3.4 (c) to 3.6 (c)). The wetting front reached an average depth of 95 cm and moved laterally to an average width of 180 cm, for the three emitter rates. The average silt plus clay content of the wetted volume was 16.3%.

iii) *Sandy clay loam*

The wetting patterns for the different emitter discharge rates on the sandy clay loam soil are given in Figures 3.7 to 3.9, and wetting front dimensions in Table 3.1.The average width to depth ratio of 3.1 shows that the width was three times the depth of distribution and water moved through the soil in a triangular distribution pattern. It is evident from the water distribution diagrams that the high silt + clay of 33.4% with a lower infiltrability resulted in more spreading of water at the surface and smaller wetting depths and volumes for both the 2 and 8 l h^{-1} emitter rates compared with the 1.2 l h^{-1}. The higher rates resulted in a smaller but wetter soil volume as the pores were more saturated with water (Bucks *et al.*, 1982). The wetting front reached an average depth of 72 cm and moved laterally to an average width of 210 cm, for the three emitter rates.

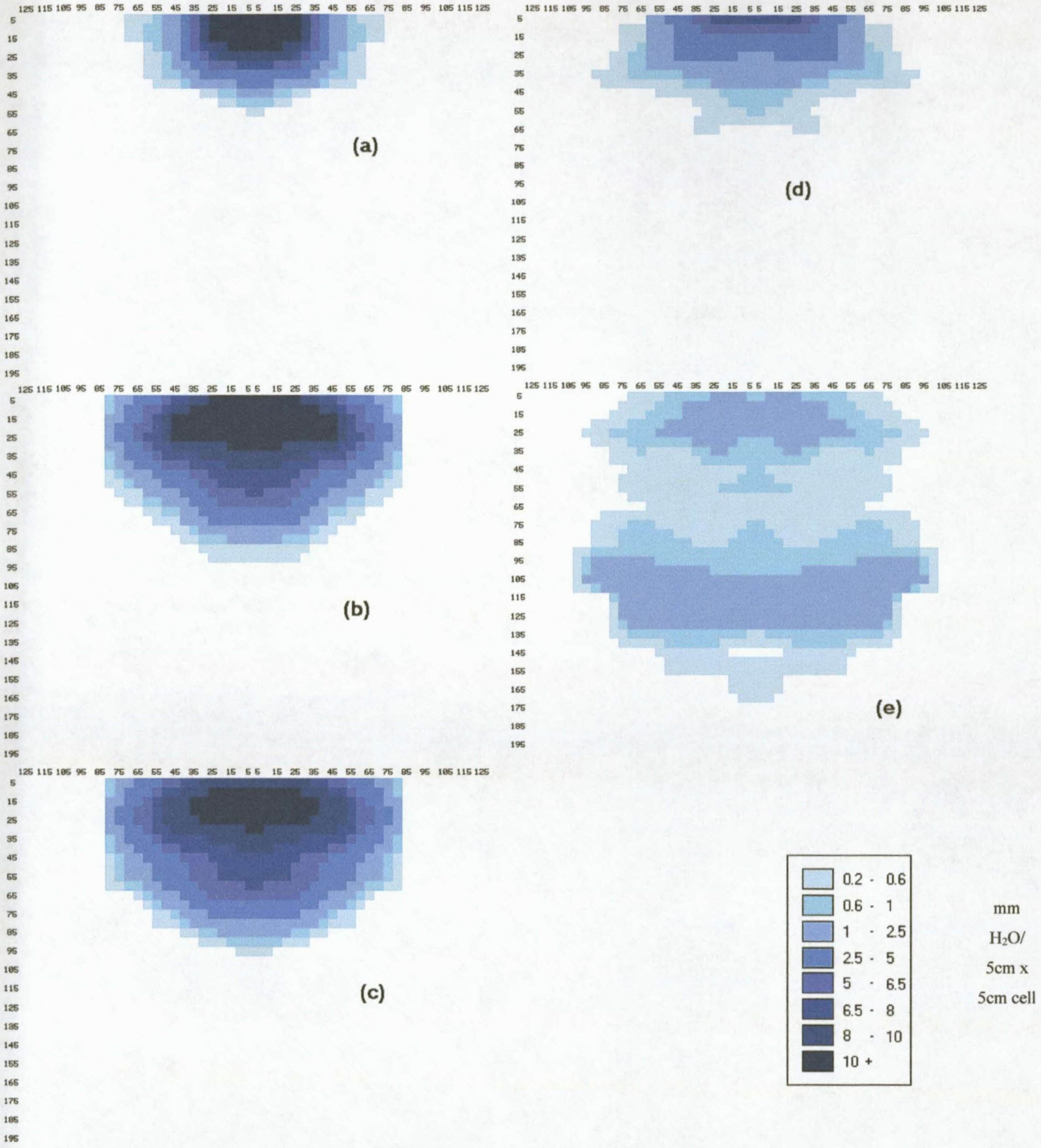


Figure 3.4 Water distribution diagrams for the luvic fine sand, with emitter discharge rate of 1.2 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil and (e) redistribution after 20 mm irrigation on a wet soil.

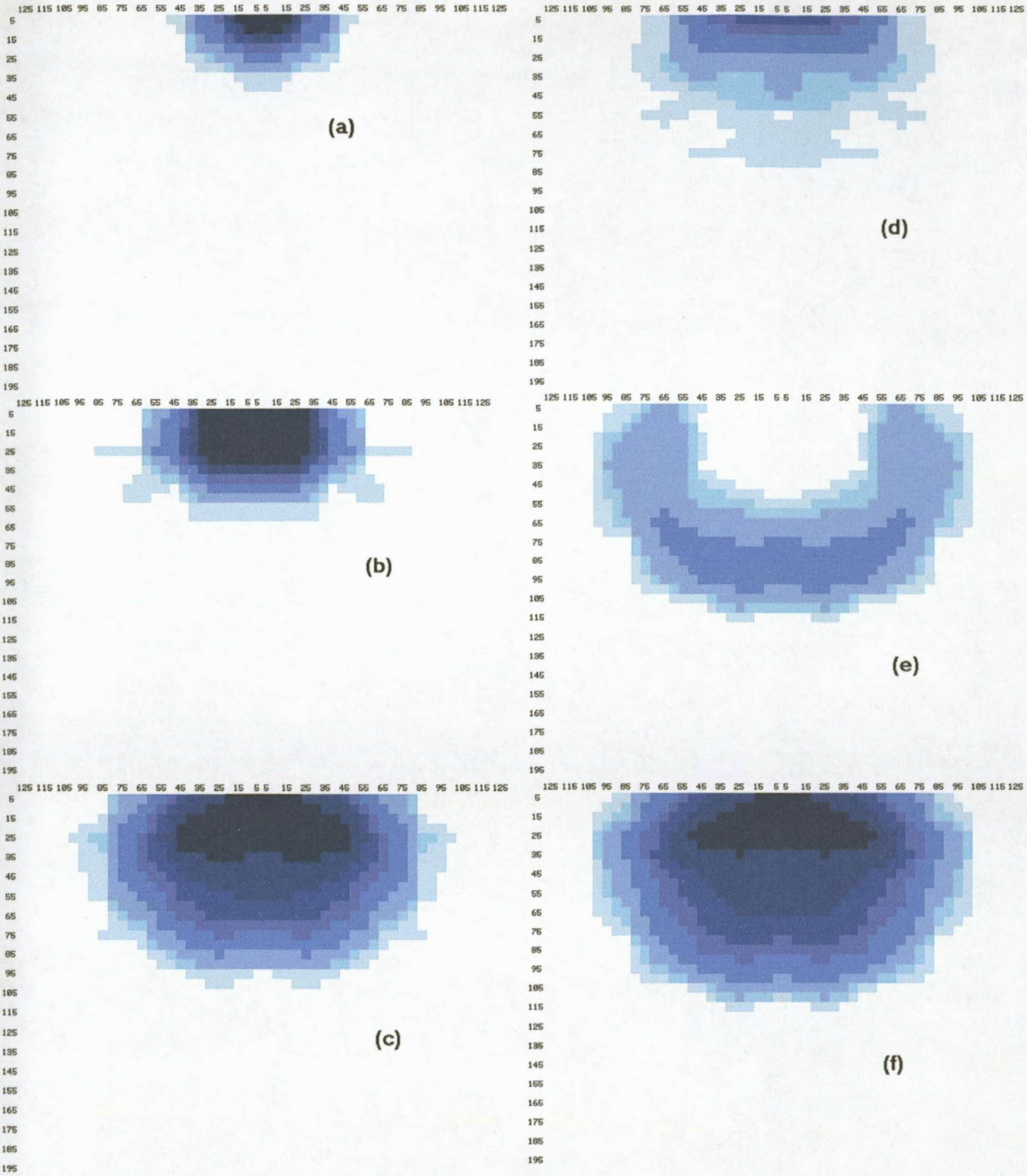
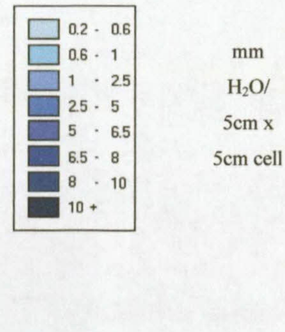


Figure 3.5 Water distribution diagrams for the luvic fine sand, with emitter discharge rate of 2 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



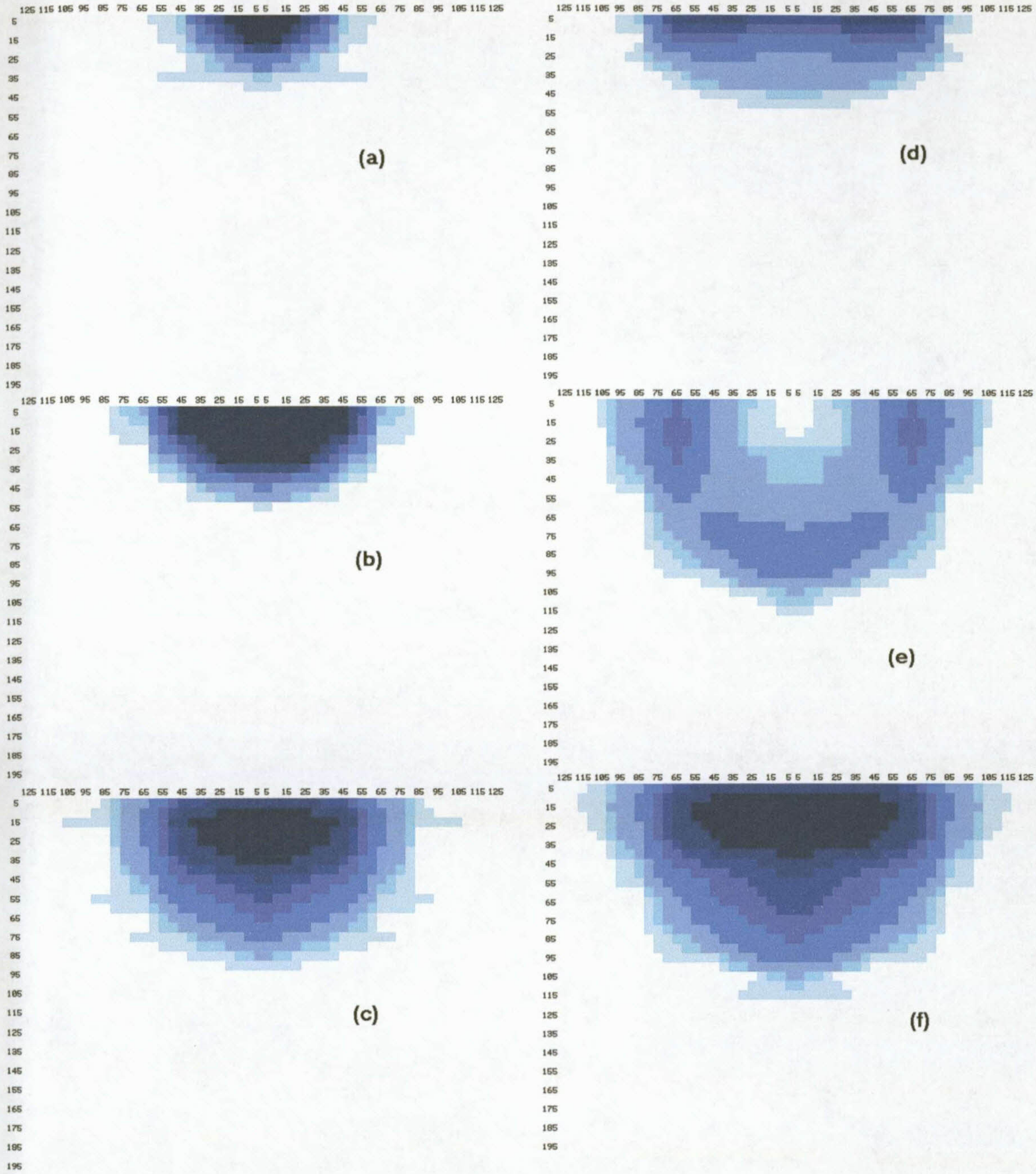
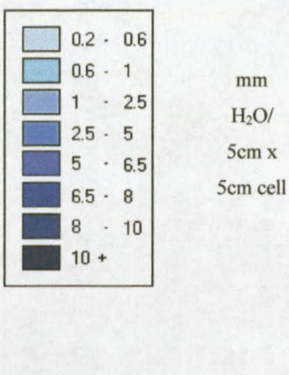


Figure 3.6 Water distribution diagrams for the luvic fine sand, with emitter discharge rate of 8 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



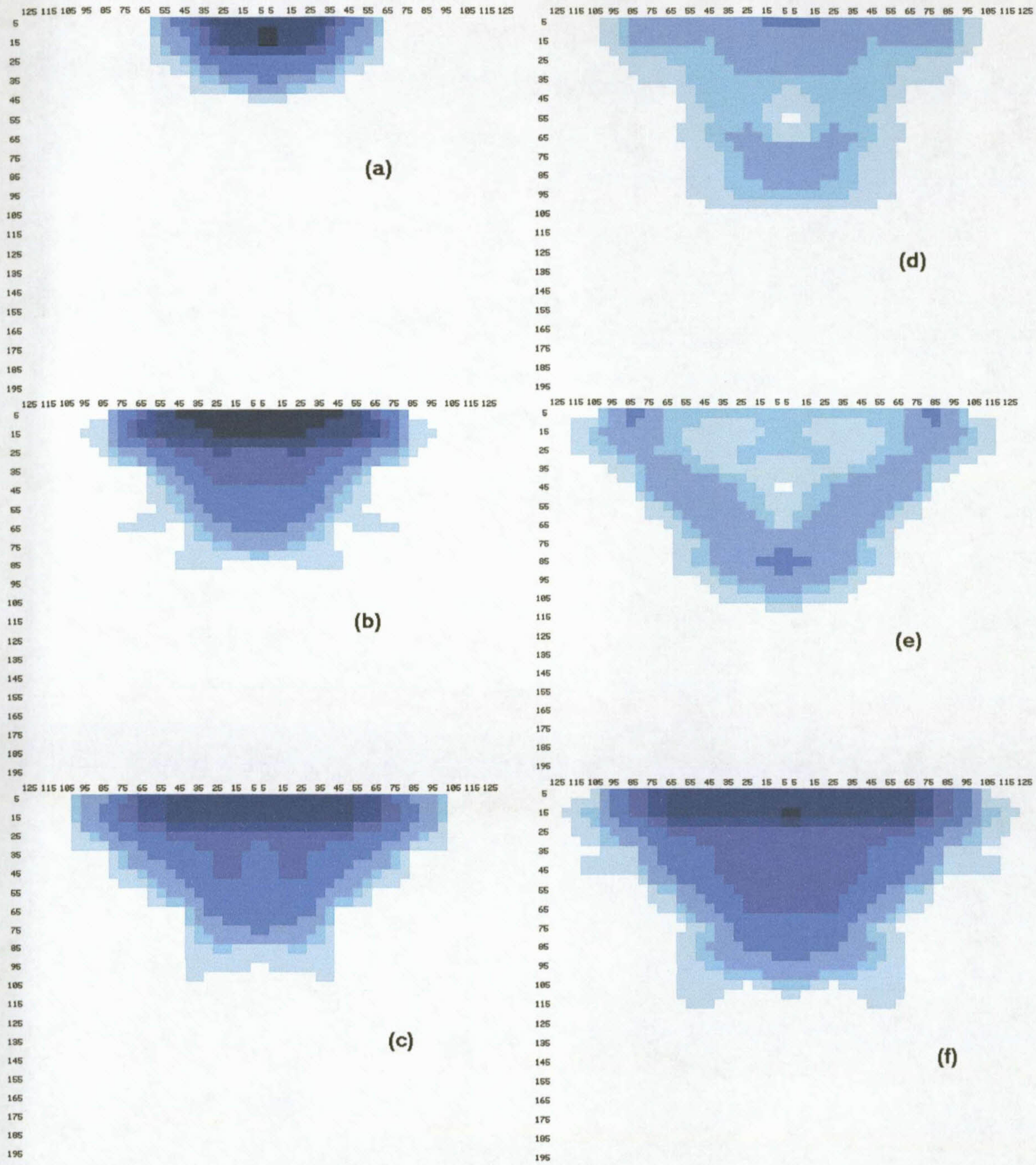
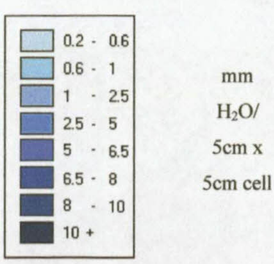


Figure 3.7 Water distribution diagrams for the sandy clay loam, with emitter discharge rate of 1.2 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



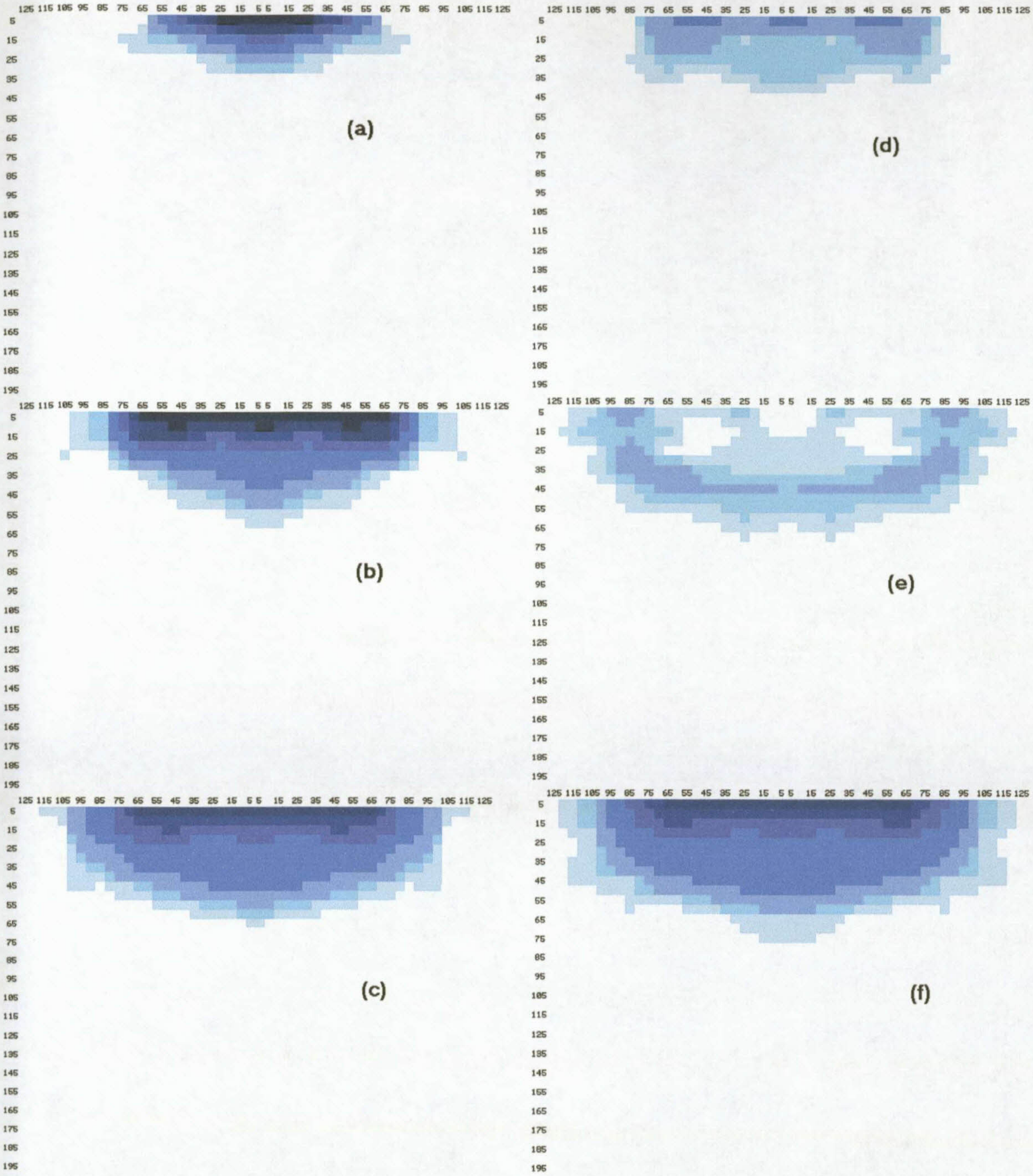
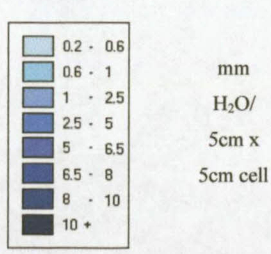


Figure 3.8 Water distribution diagrams for the sandy clay loam, with emitter discharge rate of 2 l h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



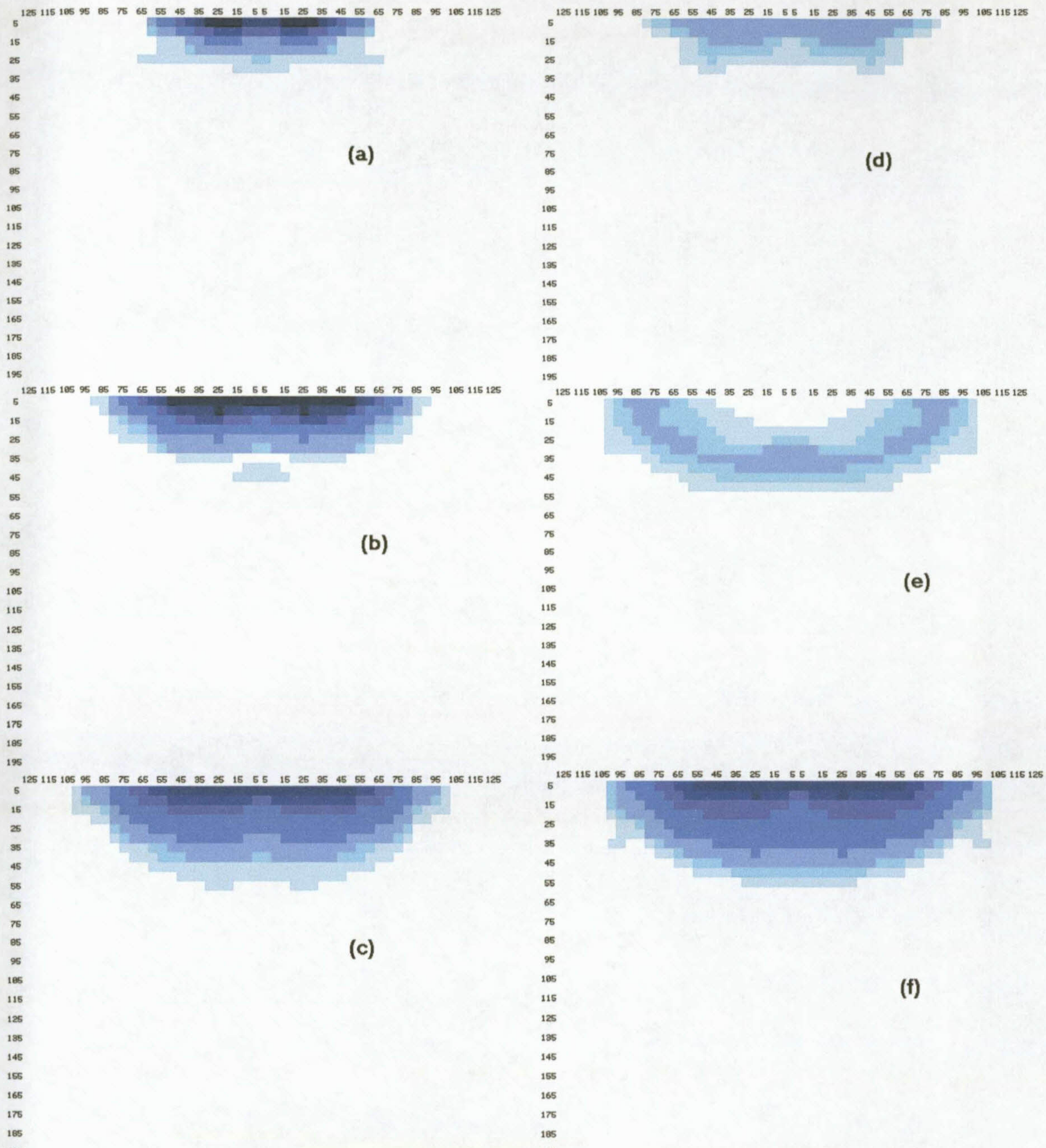
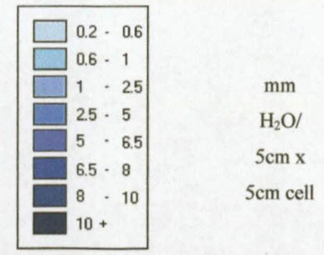


Figure 3.9 Water distribution diagrams for the sandy clay loam, with emitter discharge rate of 8 *l* h^{-1}. Each diagram indicating the amount of water gained (mm) in each cell as shades of blue. The symbol on each diagram represents distribution after a) 20mm irrigation (b) 50mm irrigation, (c) redistribution after 50mm irrigation, (d) 20 mm irrigation on a wet soil, (e) redistribution after 20 mm irrigation on a wet soil and (f) total redistribution after both irrigations.



It is clear from the preceding discussion that soil texture had a major impact on the distribution of water under the emitters. The width : depth ratio of the wetted volume emphasizes the shape of the distribution pattern. The higher the ratio, the flatter and wider the water distribution. Soil texture affected both the depth and width of distribution. This ratio increased with an increase in the percentage silt + clay for all the emitter rates, as indicated in Figure 3.10. The width : depth ratio was also a function of the emitter discharge rate as indicated by separate relationships for the 1.2 l h^{-1} and the 2 and 8 l h^{-1}, that could be combined.

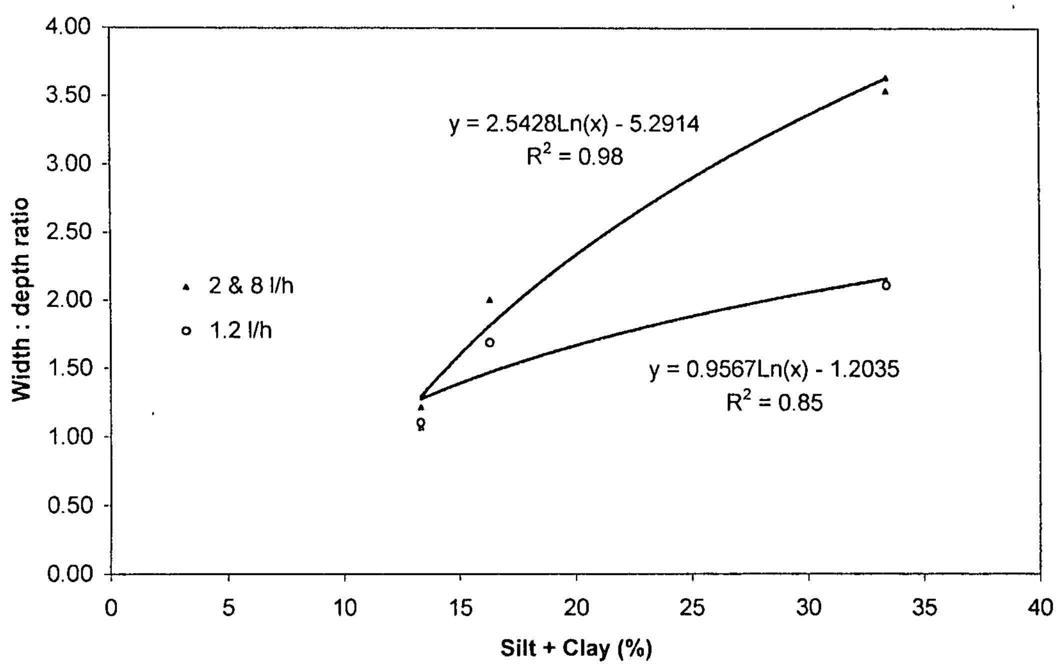


Figure 3.10 Relationship between silt + clay content and the width : depth ratio of the wetting pattern after 50mm irrigation was applied following redistribution.

Table 3.1 Dimensions of the wetted profiles for the different emitter rates and soil types

20mm irrigation (dry)		Non-luvic fine sand				Luvic fine sand				Sandy clay loam		
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	65	60	50	58.3	55	40	40	45.0	45	30	30	35.0
Wetting width (cm)	100	110	140	116.7	140	100	120	120.0	120	150	130	133.3
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.54	1.83	2.80	2.1	2.55	2.50	3.00	2.7	2.67	5.00	4.33	4.0
SA width (cm)	52	48	40	46.7	44	32	32	36.0	36	24	24	28.0
Silt+clay %		6-13.25		9.2		9.5-17.5		12.9		26.5-33.5		29.3
50 mm irrigation (dry)												
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	110	95	100	101.7	90	60	55	68.3	85	60	45	63.3
Wetting width (cm)	120	120	150	130.0	160	140	160	153.3	190	200	180	190.0
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.09	1.26	1.50	1.3	1.78	2.33	2.91	2.3	2.24	3.33	4.00	3.2
SA width (cm)	88	76	80	81.3	72	48	44	54.7	68	48	36	50.7
Silt+clay %		6-16.25		11.49		9.5-20		15.3		26.5-38.63		33
Redistribution after 50mm												
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	145	150	165	153.3	95	100	90	95.0	95	65	55	71.7
Wetting width (cm)	160	160	200	173.3	160	200	180	180.0	200	230	200	210.0
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.10	1.07	1.21	1.1	1.68	2.00	2.00	1.9	2.11	3.54	3.64	3.1
SA width (cm)	116	120	132	122.7	76	80	72	76.0	76	52	44	57.3
Silt+clay %		(6-17)		13.31		9.5-20.75		16.3		26.5-39.75		33.4

Table 3.1 Continue

20mm irrigation (wet)		Non-luvic fine sand				Luvic fine sand				Sandy clay loam		
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	65	65	55	61.7	60	80	50	63.3	100	40	30	56.7
Wetting width (cm)	80	140	110	110.0	170	160	190	173.3	200	160	160	173.3
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.23	2.15	2.00	1.8	2.83	2.00	3.80	2.9	2.00	4.00	5.33	3.8
SA width (cm)	52	52	44	49.3	48	64	40	50.7	80	32	24	45.3
Silt+clay %		6-13.25		9.2		9.5-19.25		14.6		26.5-38.5		32.6
Redistribution after 20 mm (wet)												
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	160	180	190	176.7	170	115	115	133.3	110	70	50	76.7
Wetting width (cm)	160	190	230	193.3	200	200	210	203.3	230	240	200	223.3
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.00	1.06	1.21	1.1	1.18	1.74	1.83	1.6	2.09	3.43	4.00	3.2
SA width (cm)	128	144	152	141.3	136	92	92	106.7	88	56	40	61.3
Silt+clay %		(6-17)		13.31		9.5-20.75		17.5		26.5-39.75		33.9
Redistribution after both irrigations (total)												
Emitter discharge rate	1.2	2	8	Average	1.2	2	8	Average	1.2	2	8	Average
Wetting depth (cm)	160	180	195	178.3		115	115	115.0	110	75	55	80.0
Wetting width (cm)	160	190	230	193.3		200	230	143.3	230	240	200	223.3
emitter spacing (cm)	60	60	60	60.0	60	60	60	60.0	60	60	60	60.0
width/depth	1.00	1.06	1.18	1.1		1.74	2.00	1.2	2.09	3.20	3.64	3.0
SA width (cm)	128	144	156	142.7		92	92	61.3	88	60	44	64.0
Silt+clay %		(6-17)		13.31		9.5-20.75		17		26.5-39.75		34.2

3.2.2.2 Wetting pattern after redistribution following a 20 mm irrigation on wet soil

The wetting patterns after 3 days of redistribution, following a 20 mm irrigation on a wet soil, for the different soils and emitter discharge rates, are illustrated in Figures 3.1 (e) to 3.9 (e). The width : depth ratios for the different wetting patterns are presented in Table 3.1.

The wetting patterns were very similar to those for a 50 mm irrigation and redistribution on a dry soil, discussed in the previous Section 3.2.2.1. It will therefore not be discussed in detail again. The depth : width ratio increased linearly with an increase in the silt plus clay percentage of the soil, at specific emitter discharge rates (Figure 3.11). The difference in this relationship for the 2 and 8 *l* h^{-1} emitters was small, allowing for developing a single relationship. When the relationships in Figures 3.10 for a dry soil and 3.11 for a wet soil are compared the only difference was in the luvic fine sand where the width : depth ratio was lower on the wet soil for all emitter rates, with an average value of 1.6. Except for the luvic soil, initial water content played a minor role in affecting the width : depth ratio.

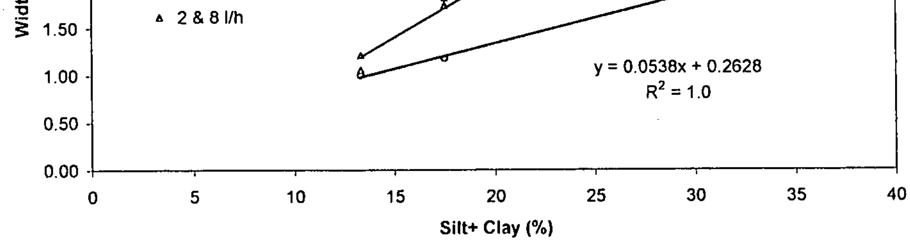


Figure 3.11 Relationship between silt + clay content and the width : depth ratio of the wetting front after redistribution following 20mm irrigation on a wet soil.

3.2.3 Effect of emitter discharge rate on the width to depth ratio of the wetting front

The wetting patterns below emitters with discharge rates of 1.2, 2 and 8 l h^{-1} are illustrated in Figures 3.1 to 3.9 for three soil types, a homogeneous fine sand, luvic fine sand and a sandy clay loam. The width : depth ratios of the different wetted patterns are given in Table 3.1.

As it was already illustrated in Figures 3.10 and 3.11, emitter discharge rate affected the width : depth ratios for specific soils, especially more clayey soils. The effect of emitter discharge rates on the wetting patterns of the different soil types requires more explanation.

i) Non-luvic fine sand

For both the dry and wet initial conditions, diagrams (c) and (e) in Figures 3.1 to 3.3, the width : depth ratio on the non-luvic fine sand increased only slightly with emitter discharge rate. This indicate that emitter discharge rate had little effect on the shape of the wetting pattern on this relatively homogeneous sandy soil.

The relationships between the width : depth ratios and emitter discharge rates for the non-luvic sand are presented in Figures 3.12 and 3.13 for the 50 mm and 20 mm irrigations respectively. The flat slopes of the relationships confirm that the width : depth ratio can be taken as a constant of approximately 1.1, irrespective of the emitter discharge rate.

ii) Luvic fine sand

For both the initial conditions, presented in diagrams (c) and (e) in Figures 3.4 to 3.6, there were a significant increase in the width : depth ratio between the 1.2 and the 2 l h^{-1} emitter rates which tended to flatten out between the 2 and 8 l h^{-1} emitters.

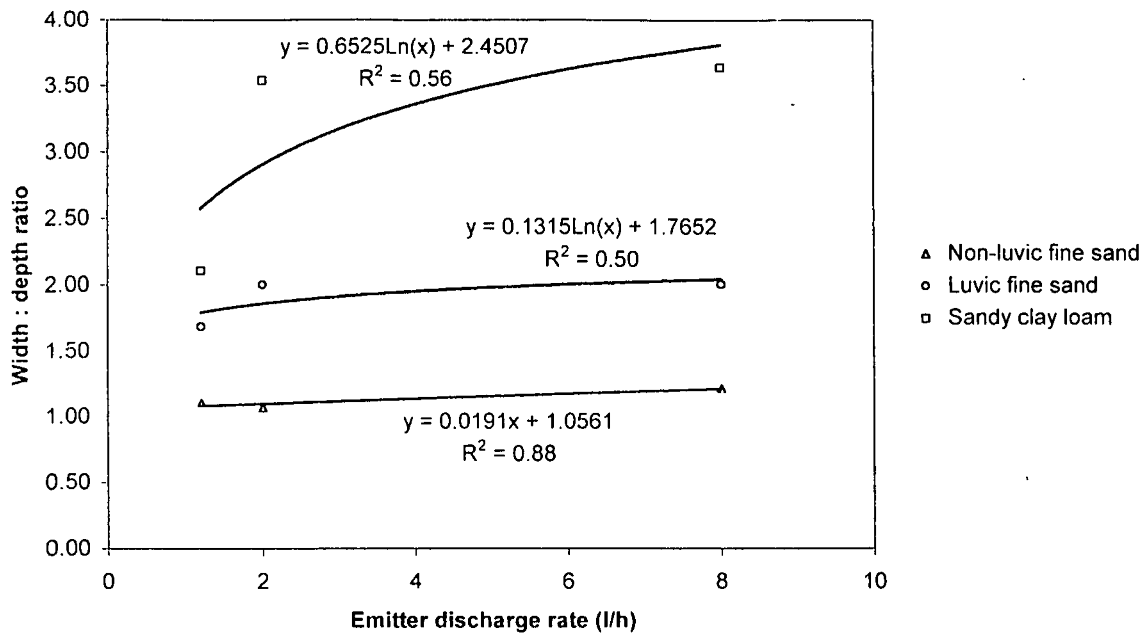


Figure 3.12 Effect of emitter discharge rate on the width : depth ratio of the wetted zone on three soil types three days after 50 mm irrigation on dry soil.

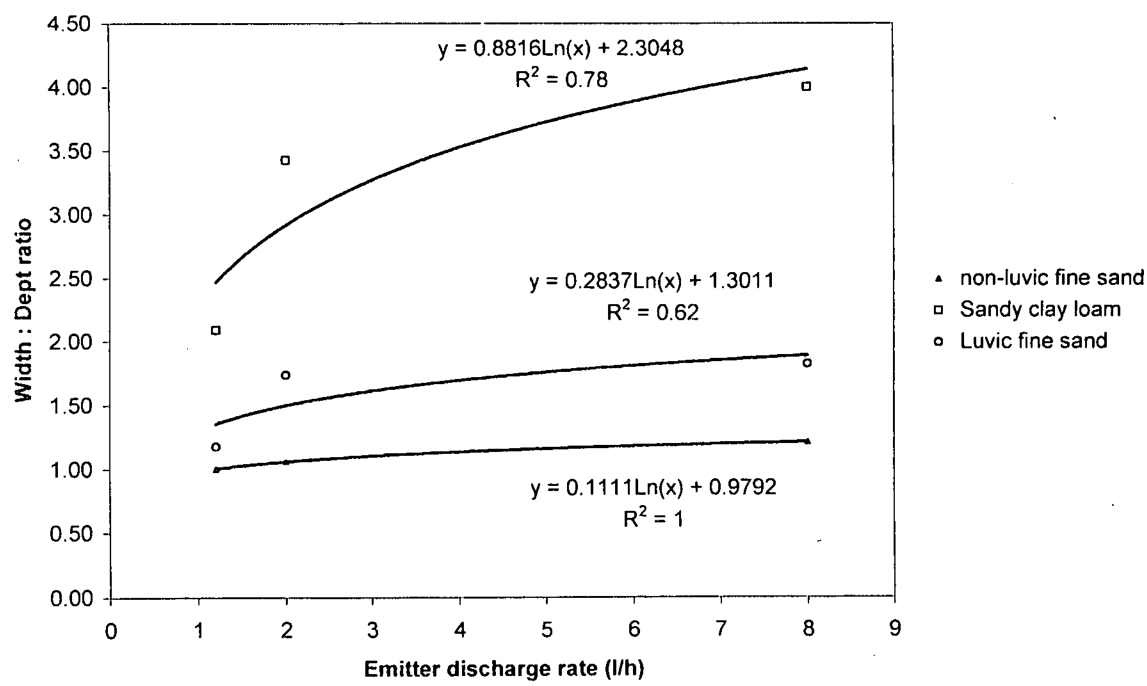


Figure 3.13 Effect of emitter discharge rate on the width : depth ratio of the wetted zone on three soil types three days after 20 mm irrigation on wet soil.

The relationships in Figures 3.12 and 3.13, for the luvic fine sand, illustrate this phenomenon. The smaller width : depth ratio below the 1.2 l h^{-1} emitters after irrigating the wet soil (Figure 3.13) resulted from a larger wetting depth of 170 cm compared with the 115 cm below the 2 l h^{-1} emitters.

iii) Sandy clay loam

For both the wet and dry initial conditions, illustrated in the diagrams (c) and (e) in Figures 3.7 to 3.9, the width : depth ratio increased sharply between the 1.2 l h^{-1} and the 2 l h^{-1} emitter rates which tended to flatten out between the 2 and 8 l h^{-1} emitters (Figures 3.12 and 3.13). This was because the depth of wetting became shallower with increasing emitter discharge rates, though the width of distribution remained similar for the different rates. Infiltration did not take place at a single point for the higher rates, because water moving across the soil surface away from the emitter during ponding continued, until the infiltration from the wetted surface equaled the emitter discharge. This resulted in the formation of a saturated circle of infinitesimal thickness around the emitter, of which the diameter increased with emitter discharge rate.

3.2.4 Effect of emitter discharge rate on the wetting depth of the three soil types

The wetting depths (Table 3.1) for the two irrigation scenarios and three soil types were plotted as functions of emitter discharge rate in Figures 3.14 and 3.15. For both the high (50mm) irrigation on a dry soil and lower (20 mm) irrigation on a wet soil, the same conclusions can be made. On the more sandy soils the wetting depth increased with an increase in emitter discharge rate. For the sandy clay loam soil with a higher clay content and lower infiltribility the opposite was true and for the luvic fine sand it had little effect. The deeper wetting depth with increasing emitter discharge rate, resulted from a larger volume of saturated soil below the emitter which favoured the downward saturated flow of water.

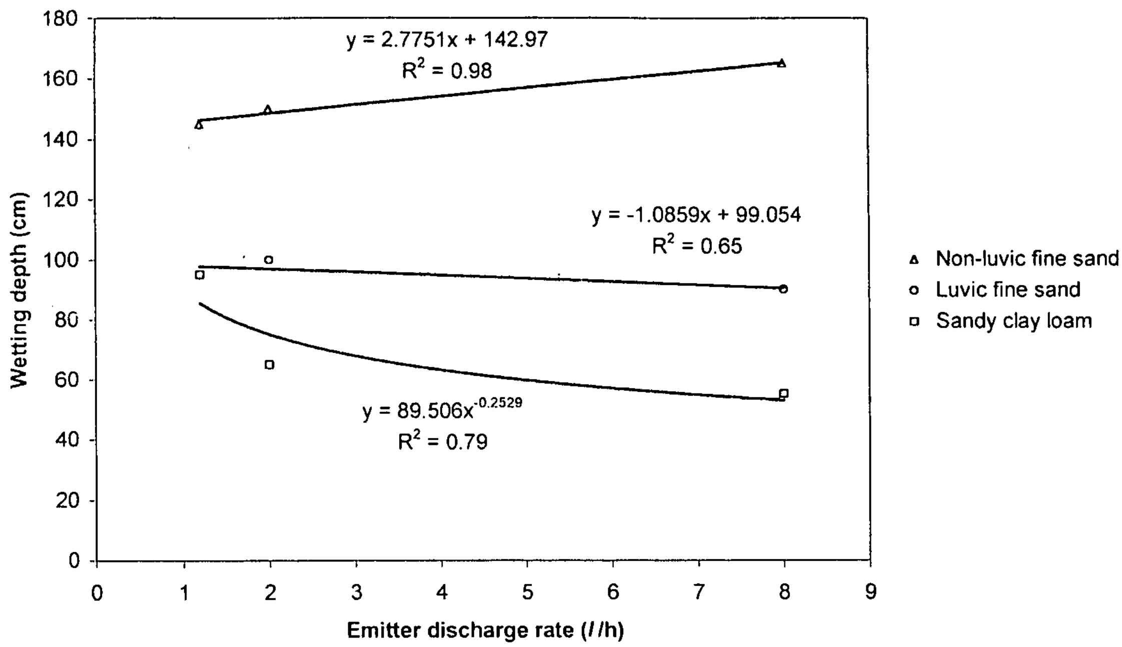


Figure 3.14 Effect of emitter discharge rate on the wetting depth for three soil types three days after 50mm irrigation on a dry soil.

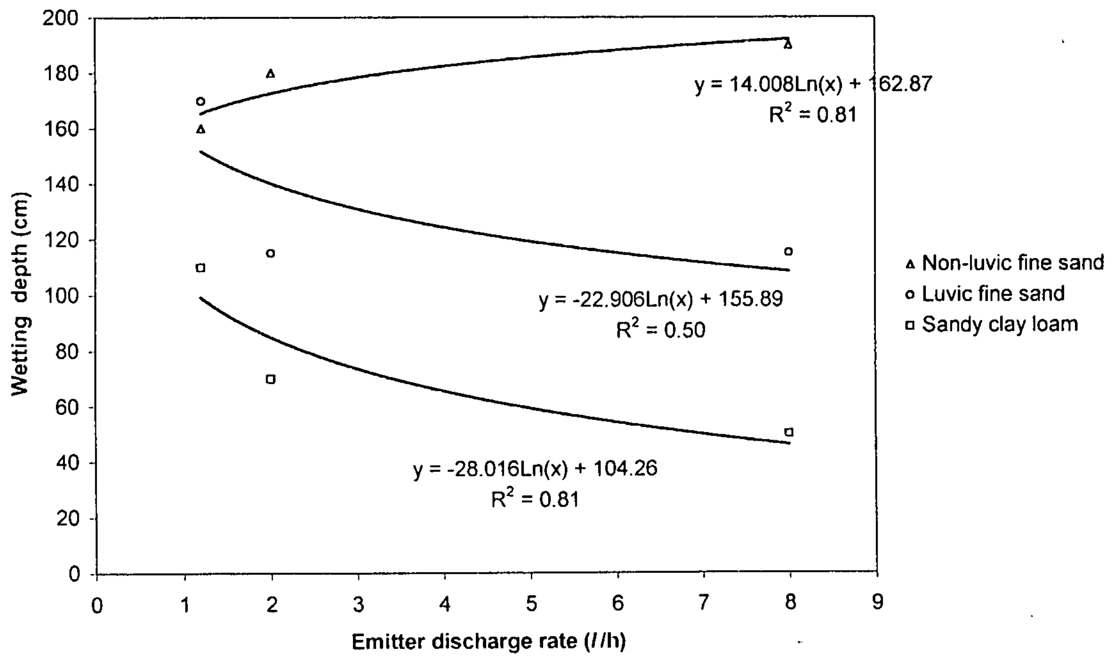


Figure 3.15 Effect of emitter discharge rate on the wetting depth for three soil types three days after 20mm irrigation on a wet soil.

3.3 Practical recommendations

i) Non-luvic fine sands

For fine sands without luvic characteristics higher emitter rates will be recommended. This will increase the wetting width substantially and although the wetting depth will also increase, plant roots should intercept the water moving downward before moving outside the root zone. The wetting depth can also be controlled by the amount of water applied per irrigation event. The higher discharge rates will result in a wider, rounder shape water distribution pattern. Because of the wider wetting volume a wider lateral spacing can be used.

ii) Luvic fine sand

For soils with a luvic character, low emitter rates will give deeper wetting depths and higher emitter discharge rates will give shallower but wider wetting. Emitter discharge rates lower or higher than 1.2 l h^{-1} can be used to modify the wetting pattern below the emitter.

iii) Sandy clay loam

In more clayey soils, the depth of wetting can become limiting. In clayey soils, with a low infiltrability, emitter discharge rates of 1.2 l h^{-1}, or lower, results in a smaller width : depth ratio with the deepest wetting and less evaporation losses from the soil surface with more water being available for plant uptake.

3.4 Conclusion

Soil texture and emitter discharge rate played an important role in the distribution of water under trickle emitters. The most acceptable way to quantify the wetted area is with the width : depth ratio of the wetting front. The width : depth ratio of the wetted volume emphasizes the shape of the distribution pattern. The higher the ratio, the flatter and wider the water distribution. This ratio increased with an increase in the silt plus clay percentage of the soil for all the emitter discharge rates. The increase was more pronounce for the emitters with a discharge rate higher than 2 l h^{-1}. The non-luvic sand, the luvic fine sand and sandy clay loam had mean ratios of 1.1, 1.6 and 3.2 respectively. The sand had the deepest wetted depth and the fast advance of the wetting front, primarily because of gravity, was due to the lower water-holding capacity and the ability of sand to conduct water faster. In the luvic soil, the 6% silt plus clay content increase at a 35 cm depth, resulted in a more saturated zone developing above 35 cm causing the width to be one and a halve times the depth of distribution. The sandy clay loam with a mean 33.4% silt plus clay content had a lower infiltrability which resulted in more spreading of water at the surface and shallower wetting depths and volumes for both the 2 and 8 l h^{-1} emitter rates compared with the 1.2 l h^{-1}. The higher emitter rates resulted in a smaller but wetter soil volume as the pores were more saturated with water.

Initial water content played a minor role in affecting the width : depth ratio, except for the luvic soil where the width : depth ratio was smaller when irrigation was applied on a wet soil.

The effect of emitter discharge rate on the width : depth ratio was different for the three soil types. For both the luvic fine sand and sandy clay loam, and for both wet and dry initial conditions, the width : depth ratio increased sharply from 1.2 l h^{-1} to 2 l h^{-1} emitter rates. This increase tended to flatten out above 2 l h^{-1}. On the non-luvic fine sand, emitter discharge rate had little effect on the width : depth ratio. On the more sandy soils the wetting depth increased with an increase in emitter discharge rate. For the sandy clay loam soil the opposite was true.

In this study wetting width was regarded as the most important consideration determining inline emitter spacing. Higher discharge rates that lead to ponding can increase surface evaporation and decrease water use efficiency. Filling of the macro pores with water to increase wetting width can adversely affect aeration, which could have a negative impact on plant growth. Definite differences exist in water content distribution within wetting patterns for different discharge rates. The relevance of these factors should be tested in a study with actively growing plants.

As a general conclusion it can be recommended that emitters with discharge rates >2 *l* h^{-1} is preferable for use on sandy soils and lower emitter discharge rates for luvic fine sands and sandy clay loams. The application of the measured width : depth ratios, of the wetted volume, will be discussed in more detail in Chapter 4.

CHAPTER 4

Proposed design criteria for trickle systems based on soil texture

4.1 Introduction

There is no fixed design criteria for trickle irrigation in South Africa, which takes the physical and hydraulic soil properties into account. The criterion for inline emitter spacing in South Africa is based on the assumption that the diameter of the wetted area below the emitter should be equal or greater than 0.8 times the wetting depth (Kleynhans, 1993). According to Kleynhans (1993) the emitter spacing on the lateral should be 80% of the wetted diameter to create a 20% overlap and therefore a continuous wetted band. Irrigation systems are often designed to an economic optimum in terms of the engineering principles, which may not produce the best environmental outcomes. There is therefore an ongoing need for assessing and continuously improving the practical guidelines for designing and managing trickle irrigation.

The same inline emitter spacing guidelines was used on all soil types. Proposals for including soil texture, more specific the coarse silt plus clay percentage, into the design guidelines will be the objective of this chapter. The sand fraction of all three soil types used in this study was predominantly fine sand. The proposed guidelines will therefore only apply to soils with predominantly fine sand in the sand fraction.

4.2 Inline emitter spacing

According to the South African design criteria (Kleynhans, 1993), the width of distribution should be equal or greater than 0.8 times the depth of distribution. That gives a width : depth ratio of 0.8. The inline emitter spacing is then calculated by allowing an additional 20% overlap. Thus if the wetting depth is known, it is multiplied by a factor 0.64 (0.8 x 0.8) to give the inline emitter spacing.

The inline emitter spacing was kept constant at 60 cm for all the experiments. A single line was used to determine the wetting width. The width : depth ratios for the three soil types and three emitter discharge rates were discussed in Chapter 3. This data will be used to compare the measured width : depth ratios with the standard 0.8 value recommended in South Africa for design purposes.

The mean of the ratios for the 1.2, 2 and 8 l h^{-1} emitter discharge rates for each soil are presented in Table 4.1. The ratios for all three soil types were higher than 0.8 and it increased with an increase in the silt plus clay percentage. It is possible that the emitter spacing of 60 cm was too small. When the emitters are spaced too close a wetted line develop which enhance lateral water distribution. It is possible that wider inline emitter spacings might effect the width : depth ratio.

Table 4.1 Comparison of the width : depth ratios of the wetting front for three soil types

	Non-luvic fine sand 6-17 % silt + clay		Luvic fine sand 9-20 % silt + clay		Sandy clay loam 26-40 % silt + clay	
	Recom	Measured	Recom	Measured	Recom	Measured
Width : depth ratio (dry)	0.8	1.1	0.8	1.9	0.8	3.1
Width : depth ratio (wet)	0.8	1.1	0.8	1.6	0.8	3.2
Emitter spacing factor (wet)	0.64	0.88	0.64	1.52 (dry) 1.28 (wet)	0.64	2.48

The dry in Table 4.1 represent conditions 3 days after a 50 mm irrigation on a dry soil and wet indicate conditions after a 20 mm irrigation on a wet soil followed by 3 days redistribution. The emitter spacing factor in Table 4.1 was calculated by multiplying the measured width : depth ratio by 0.8 to give the emitter spacing factor. Thus, if the depth of wetting is known, the maximum inline emitter spacing can be calculated by multiplying the wetting depth by the emitter spacing factor. The required wetting depth of a soil is determined by the soil depth, or potential rooting depth of the cultivated crop, which ever is the smallest. With annual crops the rooting depth increases from planting to reach maximum depths of up to 2.1 m, at the beginning of the reproductive growth stages. The effect of the required wetting depth on emitter spacing, using the measured width : depth ratio, and a 60 cm inline spacing, are compared in Table 4.2.

Table 4.2 Possible emitter inline spacing for various wetting depths

	Requied wetting depth (cm)	Measured Width : depth ratio	Emitter spacing factor (wet)	Estimated emitter spacing (cm)	Emitter spacing SA-guideline (cm)
Non-luvic fine sand Si+C (%) 6-17	60	1.1	0.88	53	38
	80	1.1	0.88	70	51
	100	1.1	0.88	88	64
	120	1.1	0.88	105	77
	140	1.1	0.88	123	90
	160	1.1	0.88	141	102
	180	1.1	0.88	158	115
Luvic fine sand Si+C (%) 9-20	40	1.6	1.28	51	26
	60	1.6	1.28	77	38
	80	1.6	1.28	102	51
	100	1.6	1.28	128	64
	120	1.6	1.28	154	77
	140	1.6	1.28	179	90
	160	1.6	1.28	205	102
Sandy clay loam Si+C (%) 26-40	20	3.2	2.56	51	13
	40	3.2	2.56	102	26
	60	3.2	2.56	154	38
	80	3.2	2.56	205	51

Practical recommendations

The effect of inline emitter spacing on the width : depth ratio of the wetting pattern need to be investigated on different soil types before the larger ratios, derived in this study, can be used for calculating the maximum inline emitter spacing. The equations that can be used to estimate the appropriate width : depth ratio for a soil from the mean silt plus clay percentage (Silt + Clay %) of the potential wetting volume, were derived in Figure 3.11. It is repeated here as Equations 4.1 and 4.2.

i) For emitter discharge rates < 2 $l\ h^{-1}$:

Width : depth ratio = 0.0538 (Silt + Clay %) + 0.26 (4.1)

ii) For emitter discharge rates > 2 $l\ h^{-1}$:

Width : depth ratio = 0.1232 (Silt + Clay %) - 0.45 (4.2)

4.3 Lateral spacing

According to Kleynhans (1993) lateral spacing is less important in South Africa because the positioning of trickle lines will normally be adapted to cultivation practices. Only a portion of the potential soil volume will thus be wetted. This could vary from 80 % wetted soil volume in row crops, to as little as 15 % for some tree crops. Certain applications, like sub surface trickle irrigation on lucerne and row crops, require that the total soil volume be wetted. With some row crops like tomatoes, paprika, onions, etc. multiple crop rows are wetted with either one or two trickle lines. Therefore it is important that guidelines exist for lateral wetting width.

A single line with a constant inline emitter spacing of 60 cm was used to determine the lateral wetting width on three soil types. Lateral wetting width measured after a 20 mm irrigation followed by 3 days redistribution on a wet soil, was used to derive Equations 4.1 and 4.2. These equations were used to calculate the width : depth ratio which gives the estimated lateral spacing, because it is representative of practical field situations.

Guidelines that can be used to estimate the appropriate lateral spacing for a specific soil, from the mean silt plus clay percentage of the potential wetting volume, are presented in Tables 4.3 and 4.4 for the 1.2 and 2 to 8 $l\ h^{-1}$ emitters respectively. The estimated wetting depth was calculated with the regression line for the relationship between silt plus clay percentage and the wetting depth (Appendix 4.1). The estimated width : depth ratio was calculated with the regression line for the relationship between silt plus clay percentage and the width : depth ratio (Figure 3.11 and Equations 4.1 and 4.2). The equation used is given at the end of each column. The estimated wetting width was calculated by multiplying the estimated wetting depth with the estimated width : depth ratio. The optimal lateral spacing was calculated by multiplying the estimated wetting width by 0.9 to create a 10% overlap and continuous wetting area.

The effect of lateral spacing on the number of emitters required per hectare, emphasize economical and practical aspects that should be considered in the design.

Table 4.3 Optimal lateral spacing for 1.2 $l\ h^{-1}$ emitters with a 60 cm inline spacing

1.2 $l\ h^{-1}$					
Silt + Clay (%)	Estimated Wetting depth (cm)	Estimated Width : depth ratio	Estimated Wetting width (cm)	Optimal lateral spacing (cm)	Emitters ha^{-1}
<10	179	0.80	143	129	12961
12	173	0.91	157	142	11792
14	168	1.02	170	153	10892
16	162	1.12	182	164	10186
18	157	1.23	193	174	9625
20	151	1.34	202	182	9177
22	145	1.45	210	189	8818
24	140	1.55	217	196	8533
26	134	1.66	223	201	8310
28	129	1.77	228	205	8141
30	123	1.88	231	208	8020
32	118	1.98	234	210	7943
34	112	2.09	235	211	7907
36	107	2.20	235	211	7912
	$y = -2.7751x + 206.53$ $R^2 = 0.88$	$y = 0.0538x + 0.2628$ $R^2 = 1.0$			

Practical recommendations

The guidelines given here are based on actual data for emitters applying 20 mm irrigation on a wet soil following redistribution with a constant inline emitter spacing of 60 cm. These criteria might change when less irrigation than this amount is applied. By using this lateral spacing, a continuous wetting area will be obtained. The question can be asked if its necessary to wet the whole area. Strip wetting such as for crops or trees in wide rows can give a better water use efficiency. The 10% overlap that was used, might not be necessary to achieve a continuous wetting area.

Table 4.4 Optimal lateral spacing for emitter discharge rates between 2 and 8 $l\ h^{-1}$ with a 60 cm inline spacing

2-8 $l\ h^{-1}$					
Silt + Clay (%)	Estimated Wetting depth (cm)	Estimated Width/depth ratio	Estimated Wetting width (cm)	Optimal lateral spacing (cm)	Emitters ha^{-1}
<10	205.7	0.78	161	145	11508
12	183.0	1.03	189	170	9841
14	163.8	1.28	209	188	8871
16	147.2	1.52	224	202	8275
18	132.6	1.77	235	211	7909
20	119.5	2.02	241	217	7704
22	107.6	2.26	243	219	7621
24	96.8	2.51	243	219	7641
26	86.8	2.76	239	215	7755
28	77.6	3.00	233	210	7964
30	69.0	3.25	224	202	8274
32	61.0	3.49	213	192	8702
34	53.5	3.74	200	180	9275
	$y = -124.36Ln(x) + 492.02$ $R^2 = 0.90$	$y = 0.1232x - 0.448$ $R^2 = 1.0$			

4.4 Conclusion

The width : depth ratios for the three soil types and three emitter discharge rates were used to compare the measured width : depth ratios with the standard 0.8 value recommended in South Africa for design purposes. The ratios for all three soil types were higher than 0.8 and it increased with an increase in the silt plus clay percentage. The emitter spacing factor was calculated by multiplying the measured width : depth ratio by 0.8 to give a 20% overlap and create a continuous wetting strip. Thus, if the depth of wetting is known, the inline emitter spacing can be calculated by multiplying the depth by the emitter spacing factor.

The following emitter spacing factors could be used to determine the inline emitter spacing:

- Non-luvic fine sand 0.88
- Luvic fine sand 1.28
- Sandy clay loam 2.56

The effect of inline emitter spacing on the width : depth ratio of the wetting pattern need to be investigated on different soil types before the larger ratios, derived in this study, can be used for calculating the inline emitter spacing. Equations 4.1 and 4.2 can be used to estimate the appropriate width : depth ratio for a soil, from the mean silt plus clay percentage (silt + clay %) of the potential wetting volume.

The relationship between the soil texture (silt + clay %) and wetting depth and width : depth ratio was used to estimate the wetting depth, depth : width ratio, wetting width, the optimal lateral spacing and the number of emitters per hectare. The guidelines given here is based on the silt plus clay content of soils and were derived from actual data for emitters applying 20 mm irrigation on wet soil following redistribution with a constant inline emitter spacing of 60 cm. By using this lateral spacing, a continuous wetted area should be obtained. Care should be taken that these recommendations are only used on soils where the sand fraction is dominated by fine sand.

CHAPTER 5

Effect of application timing on the distribution of nitrate in fertigated soils

5.1 Introduction

Fertigation refers to the application of fertilizers through irrigation. This practice is gaining popularity as an efficient way of supplying soluble plant nutrients to the root system. Fertigation decrease labour costs and with proper management practices it can decrease nutrient losses from the root zone through leaching. Limiting excessive leaching of the fertilizer is also necessary to prevent groundwater pollution.

A good understanding of solute transport in either two or three dimensions, below the emitter or point source, is required to develop efficient strategies for fertigation management. Because of high fertilizer costs, it is important that applied nutrients through emitters should be available to the largest fraction of the root system.

Bristow *et al.* (2000) used non-reactive ion applications to mimic nitrate movement. The effect of application timing of these types of ions, on the distribution pattern in three soils types with subsurface trickle irrigation, was simulated with a computer model. Timing of solute application did not have much of an influence on solute transport on silty and duplex soils because the water and solute stayed close to the emitter. They found that in the sand, timing of application and initial water content had a major impact on solute transport. Firstly the solute was applied for an hour after the sand had been wetted for 4 hours. After injection of the solute pulse, they noticed elliptical pockets of solute forming below the emitter, which continued to move downwards. Secondly the solute was applied in the beginning of the irrigation cycle on a dry soil. The concentration patterns were more circular than elliptical, with pockets of solute forming above the subsurface emitter. They suggested that for sandy soils, applying solutes in the beginning of an irrigation cycle is better to achieve the goal of increasing water and nutrient use efficiency, and reducing the risk of chemical leaching from the root zone.

The effect of the time of nitrate application during an irrigation event on the nitrate movement in the soil, was the objective of this part of the study. Only the luvic sand with an emitter discharge rate of 2 l h^{-1} was used for this purpose. The procedures that were used was discussed in Section 2.6. The treatments were as follows: Firstly nitrate was injected into the irrigation water in the beginning of a 20 mm irrigation event and four days later a second irrigation of 20 mm was applied. In the second experiment the nitrate was injected into the irrigation water at the end of a 20 mm irrigation event. Four days later a further 20 mm irrigation was applied.

The nitrate distribution patterns are presented in Figures 5.1 to 5.3. Figure 5.1 illustrate the nitrate distribution for both application timings below the emitter at the end of the first (a and c) and second (b and d) second irrigation events. Figure 5.2 give the nitrate distribution between two emitters and Figure 5.3 give the average values.

5.2 Nitrates applied at the beginning of an irrigation event

When nitrate was applied on a dry soil at the beginning of an irrigation event, the nitrates tended to move away from the emitter in a horse shoe shape with the highest concentration in the top 20 cm about 30 cm away from the emitter (Figure 5.1a). Similar results were found by Bristow *et al.* (2000). Most nitrates concentrated between the two emitters where the wetting circles overlap, where it reached a concentration of 161 mg NO_3^- kg^{-1} soil at a depth of 15cm (Figure 5.2a and Appendix 5.1)).

Total applied nitrates (mg kg^{-1}) for each column, 5, 25, 45, 65 & 85 cm from the emitter for one quadrant are presented in Table 5.1. Table 5.1 illustrates nitrate distribution after

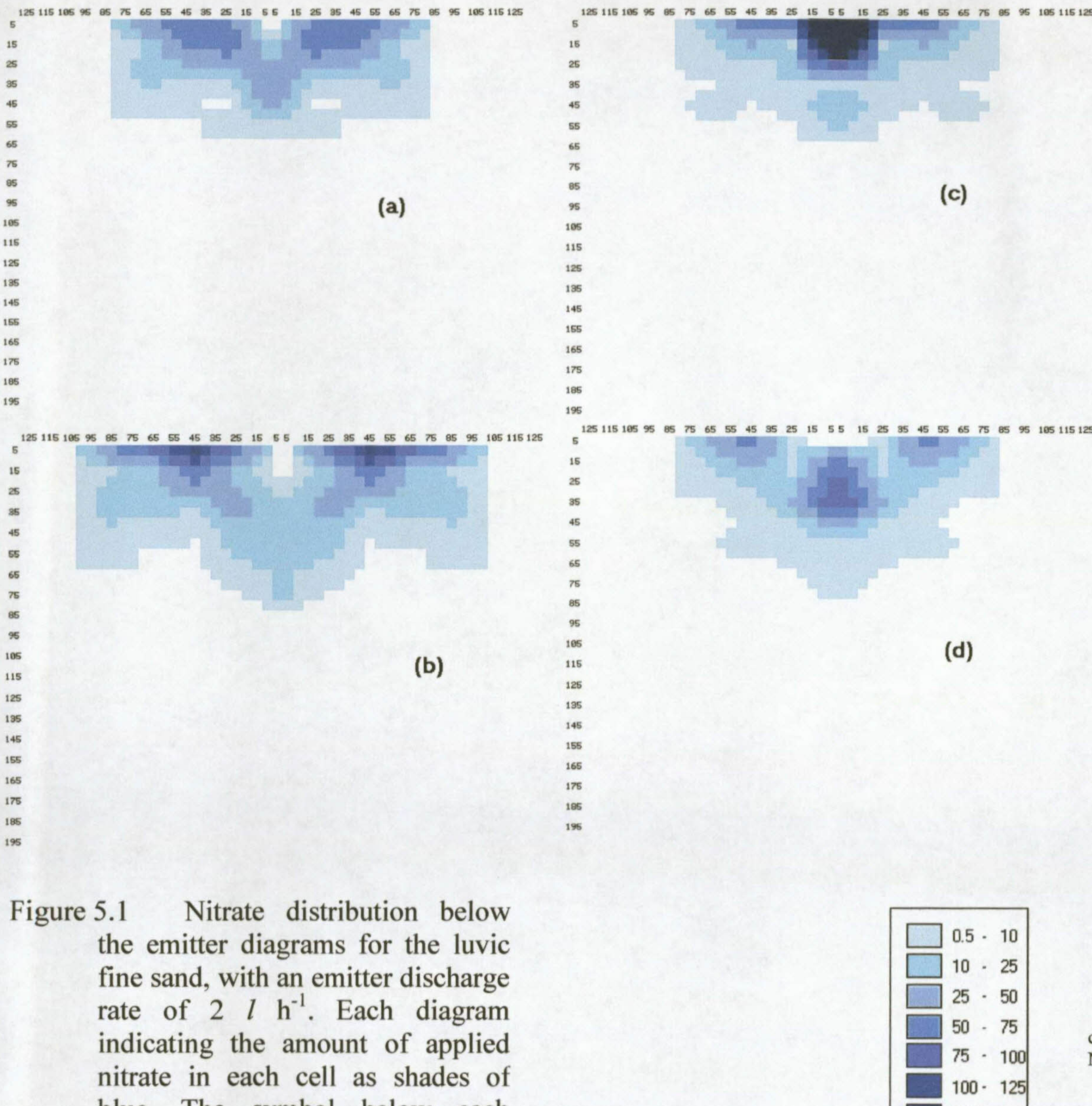
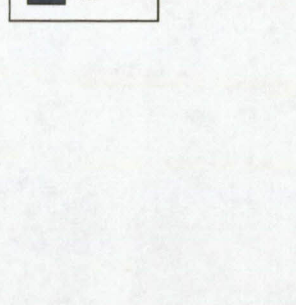


Figure 5.1 Nitrate distribution below the emitter diagrams for the luvic fine sand, with an emitter discharge rate of 2 l h^{-1}. Each diagram indicating the amount of applied nitrate in each cell as shades of blue. The symbol below each diagram represents nitrate applied in a) the beginning of the event and (b) after an additional 20mm irrigation, (c) end of the event and (d) after an additional 20mm irrigation.



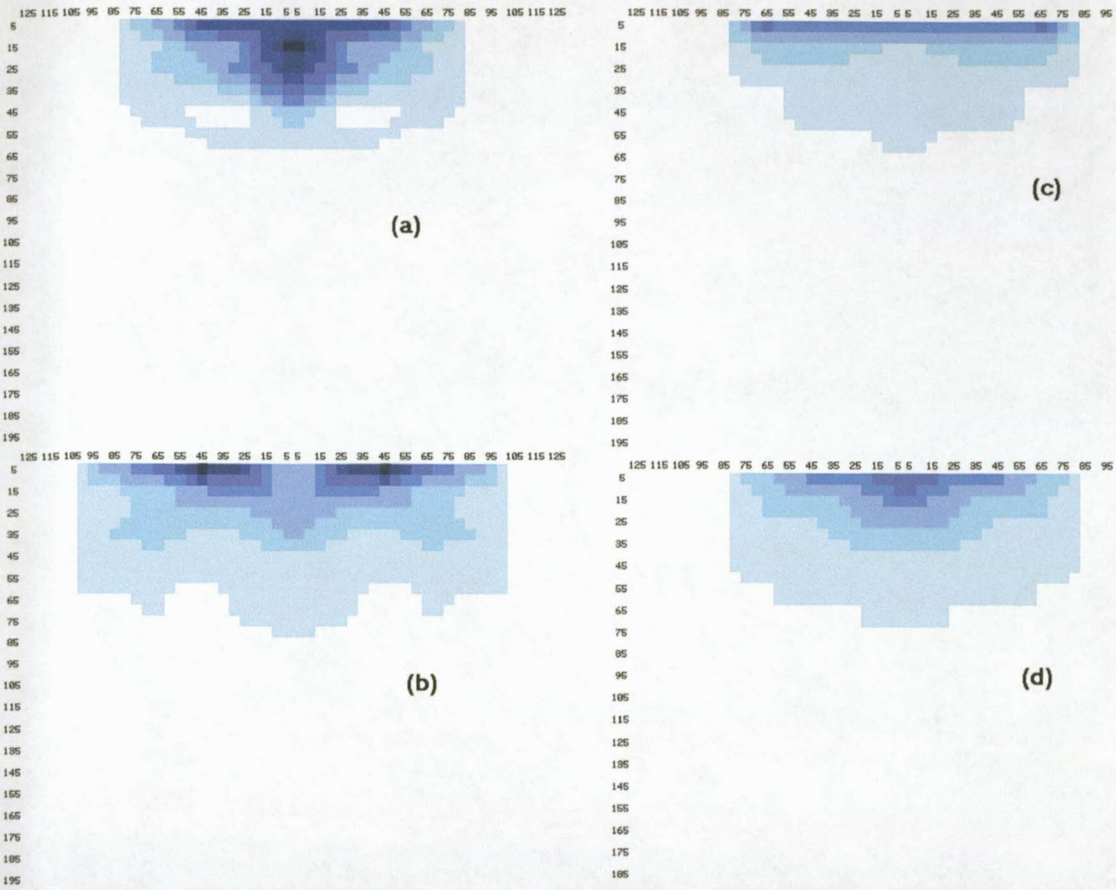
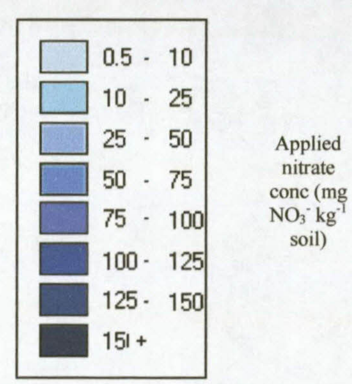


Figure 5.2 Nitrate distribution between emitters diagrams for the luvic fine sand, with an emitter discharge rate of 2 l h^{-1}. Each diagram indicating the amount of applied nitrate in each cell as shades of blue. The symbol below each diagram represents nitrate applied in a) the beginning of the event and (b) after an additional 20mm irrigation, (c) end of the event and (d) after an additional 20mm irrigation.



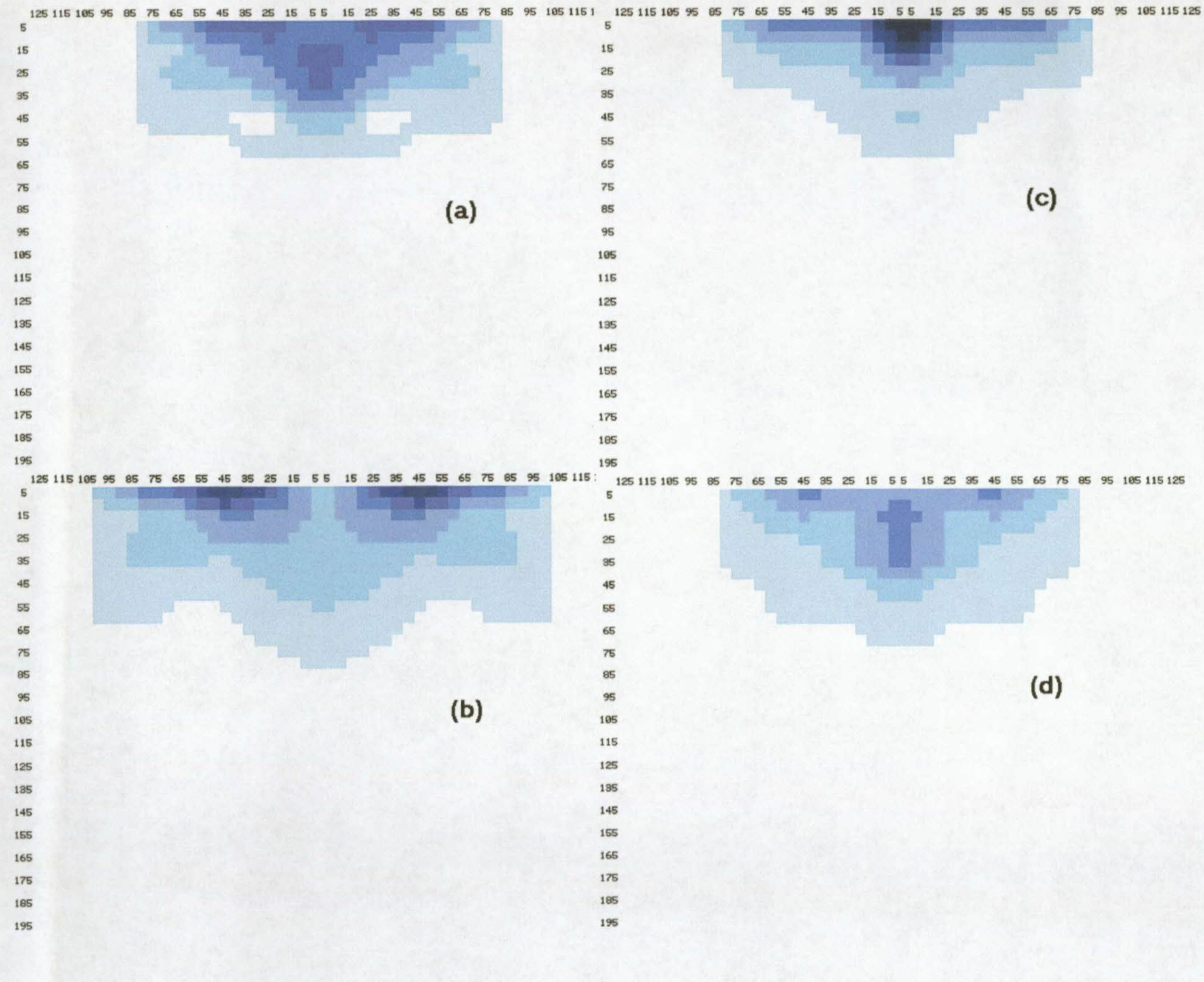
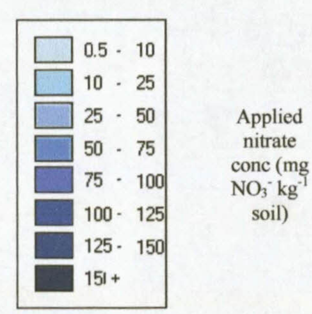


Figure 5.3 Average nitrate distribution diagrams for the luvic fine sand, with an emitter discharge rate of 2 *l* h^{-1}. Each diagram indicating the amount of applied nitrate in each cell as shades of blue. The symbol below each diagram represents nitrate applied in a) the beginning of the event and (b) after an additional 20mm irrigation, (c) end of the event and (d) after an additional 20mm irrigation.



being injected at the beginning or end of the first 20 mm irrigation, followed by 3 day redistribution and after an additional 20 mm irrigation, followed by 3 day redistribution.

Table 5.1 Average applied nitrate concentration (mg NO_3^- kg^{-1} soil) at various distances from the emitter

Distance from emitter (cm)	Nitrate injected at beginning of first 20 mm irrigation followed by 3 days redistribution	After second 20mm irrigation plus 3 days redistribution	Nitrate injected at end of first 20 mm irrigation followed by 3 days redistribution	After second 20mm irrigation plus 3 days redistribution
5	45.16	14.37	73.28	36
25	35.28	28.81	16.46	15.51
45	26.84	40.14	19.12	17.48
65	14.15	26.81	12.94	9.47
85		14.13		

When considering the average distribution in Figure 5.3 (a), the applied nitrates spread much more evenly through the first 45 cm from the emitter As indicated in Table 5.1, the highest NO_3^--concentration occurred below the emitter (5 cm from emitter) and it decrease away from the emitter. When nitrate was injected at the beginning of the first 20 mm irrigation followed by 3 days redistribution, the nitrate front reached a depth of 60 cm and moved laterally to 80 cm from the emitter.

After an additional 20 mm of water was applied, the distribution pattern changed and more lateral movement occurred (Figure 5.1 (b)). The mean applied nitrate for the column 5 cm away from the emitter, reduced from 45.16 to 12.67 mg NO_3^- kg^{-1} soil (Table 5.1). It is clear that nitrates spread more evenly away from the emitter after an additional 20 mm irrigation was applied (Table 5.1). The nitrate front reached a depth of 80 cm and moved laterally to about 100 cm from the emitter.

Practical considerations

When considering the average distribution (Figure 5.3) it is clear that nitrates spread more evenly and laterally away from the emitter when nitrate was applied in the beginning of an irrigation event. This timing of application is best for crops where a single emitter supply nitrate to more than one plant.

5.3 Nitrates applied at the end of an irrigation event

When the nitrate was applied at the end of an irrigation event, on wet soil, most of the nitrates (439 mg NO_3 kg^{-1} soil in the column 5 cm from the emitter) stayed close to the emitter with some lateral movement in the top 5 cm to about 50 cm away (Figure 5.1 (c) and Table 5.1). This can clearly be seen in the graph for the distribution between 2 emitters (Figure 5.2 (c)). The nitrates below the emitter moved downward to about 25 cm depth, but the highest concentration (421.75 mg NO_3^- kg^{-1}) stayed right below the emitter (Appendix 5.1). From the average NO_3^- -concentrations in Table 5.1, it is clear that most of the applied NO_3^- stayed below and near the emitter.

After an additional 20mm of water was applied, the high concentration of nitrates right below the emitter tended to move downward to a depth of about 45 cm, with a highest concentration of about 103.55 mg NO_3 kg^{-1} soil at a depth of 35 cm. The average nitrate concentration around the emitter reduced from 73.28 to 36 mg NO_3 kg^{-1} soil. The balance concentrated in the top 10 cm of the soil, 35 cm away from the emitter (Table 5.1). The nitrate front reached a depth of 60 cm and width of 80 cm. Thus when nitrates were applied at the end of the irrigation event, the movement was not as deep and wide and most nitrates stayed close to the emitter compared to when it was applied at the beginning.

Practical considerations

From Figure 5.3 it is evident that the majority of the nitrates tended to stay near the emitter when nitrates was applied at the end of an irrigation event. The application of nitrates at the end of an irrigation event is recommended for trees and crops where more than one emitter is used to apply nitrates to a single plant. High application rates might cause root and seed damage and should be taken into consideration.

5.4 Conclusion

When nitrate was applied in the beginning of an irrigation event the distribution of nitrate was much more even throughout the profile with more lateral movement than when applied at the end of an irrigation event. When an additional 20 mm irrigation was added 3 days later on the treatment where nitrate was applied in the beginning, pockets of nitrate formed in the top 20 cm of the profile, 20-60 cm away from the emitter. When rain follows fertigation, these pockets might move downward.

When the nitrate was applied at the end of an irrigation event, the majority of nitrate stayed below the emitter with little movement sideways. When an additional 20 mm irrigation was applied 3 days later, the majority of nitrate moved downwards with some lateral movement.

It is recommended that when the emitters are placed between two rows of crops, or where a single emitter feed more than one plant, that nitrate should be applied in the beginning of an irrigation event. When the emitters are next to the crop row or trees, or when more than one emitter feed a single plant, it is recommended that nitrate should be applied at the end of an irrigation event.

Aspects that require further attention are:

- How must we fertigate to prevent leaching of nitrogen?
- How will effective rooting depth of the crop influence the method of nitrate fertigation?
- Should the method of fertigation be taken into consideration when deciding on an inline emitter spacing?

CHAPTER 6

Summary and conclusions

Trickle irrigation has become a common practice in agricultural production in the world, as it is seen as one way of achieving sustainable irrigation management practices. If we want to achieve sustainable irrigation management practices, trickle irrigation systems must be designed and operated effectively. Water and fertigated solutes (fertilizers and chemicals) must be applied effectively to maximize water and nutrient uptake by crops, and to minimize leaching of nutrients and chemicals from the root zone.

The first objective of this study was to quantify the dimensions of the wetted volume below the emitters of trickle irrigation for three soil types, and to extrapolate this data so that it could be applied on more soil types. Three different soil types, a non-luvic fine sand (6-17% silt plus clay), *luvic fine sand (9.5-20.75% silt plus clay) and sandy clay loam (26.5-39.75% silt plus clay)) and three emitter discharge rates 1.2, 2 and 8 $l\ h^{-1}$ were used to determine the water distribution pattern below trickle emitters. Neutron probe access tubes were installed in a straight line perpendicular with an emitter at distances of 5, 25, 45, 65, 85, 105, 125 and 145 cm away from the emitter and between two emitters with the same distance from the line, to depths of 1.8 m, to get accurate average readings over the whole wetted area including the overlap.

The water content, expressed in mm water per 100 mm soil depth, was measured with a neutron probe at 10 cm depth intervals till a depth of 155 cm, for each access tube. Measurements were taken before each irrigation event started and these readings were used as a control. After a given amount of water was applied, or following redistribution, readings were taken again at the same depths. The average value for the readings, perpendicular with the emitter and between the 2 emitters, were used to calculate the gains in water content at each of the depths by subtracting the control.

* Refers to soil where the increase in clay content from the sandy A-horizon to the apedal B-horizon is more than 5%. This phenomenon gives rise to a significant decrease in hydraulic conductivity in sandy soils that appears to be homogeneous.

For the first irrigation event of 50mm, neutron probe readings were taken after 10mm, 20mm, 30mm and 50mm irrigation was applied. Water gained in each 5x10x10 cm (measurements 5 cm away from emitter) and 20x10x10 cm (measurements at 25, 45, 65, 85 etc. cm away from the emitter) cells were determined by subtracting the control from the measured water content. With this method, water movement could be expressed in a grid-like pattern in a two dimensional plane for one quadrant. The wetting patterns were presented in a diagram, indicating the increase in water content in each cell as shades of blue. The opposite quadrant was assumed to be symmetrical. Interpolation was used to reduce the cell sizes to 5x5x5 cm. A computer program was written to perform this task.

Soil texture and emitter discharge rate played an important role in the distribution of water under trickle emitters. The most acceptable way to quantify the wetted area was the ratio between the width and depth of the wetting front. The width : depth ratio of the wetted volume emphasizes the shape of the distribution pattern. The higher the ratio, the flatter and wider the water distribution. It was found that this ratio increased with an increase in the average silt plus clay percentage of the wetted soil for all the emitter discharge rates. This effect of texture was more pronounce for emitters with a discharge rate of 2 l h^{-1} and higher.

The non-luvic sand, the luvic fine sand and sandy clay loam had width : depth ratios of 1.1, 1.6 and 3.2 respectively, which were all higher than the minimum of 0.8, as mentioned by Kleynhans (1993). The sand wetted the deepest and the fast downward movement of the wetting front, was a result of a lower water-holding capacity and the ability of sand to conduct water faster. In the luvic soil, the sharp increase in clay content at a depth of 35 cm resulted in a more saturated zone developing above the boundary causing the width to be one and a halve times the depth of water distribution. The sandy clay loam with the highest average silt plus clay percentage of 33.4% in the wetted zone and lowest infiltrability, resulted in more spreading of water at the surface giving rise to shallower wetting depths and smaller wetted volumes for both the 2 and 8 l h^{-1} emitter rates compared with the 1.2 l h^{-1}. The higher application rates resulted in smaller but wetter soil volumes as the pores were more saturated with water.

Initial water content had a minor affect on the width : depth ratio, except for the luvic soil where the width : depth ratio was lower on the wet soil for all emitter rates with an average width : depth ratio of 1.6.

The effect of emitter discharge rate on the width : depth ratio was different for the three soil types. For both the luvic fine sand and sandy clay loam, irrespective of initial wetness, the width : depth ratio increased sharply from the 1.2 l h^{-1} to the 2 l h^{-1} emitter rates after which it remained the same to 8 l h^{-1} emitters. On the non-luvic fine sand emitter discharge rate had little effect on the width : depth ratio.

Emitter discharge rates affected the wetting depths on the more sandy soils and the wetting depth increased with an increase in emitter discharge rate. For the sandy clay loam soil the opposite was true and for the luvic fine sand it had little effect. If width of distribution is the most important consideration, higher emitter rates is preferable on sandy soils and lower emitter rates for both the luvic fine sands and sandy clay loams.

Because design criteria for trickle irrigation systems in South Africa presently do not take the physical and hydraulic soil properties into account, there was a need to evaluate the guidelines for designing and managing trickle irrigation on different soil types. This was the second objective of this study. The criterion for inline emitter spacing in South Africa is based on the assumption that the diameter of the wetted area below the emitter should be 0.8 times the wetting depth. The emitter spacing on the lateral should be 80% of the wetted diameter to create a 20% overlap and therefore a continuous wetted band.

The inline emitter spacing was kept constant at 60 cm for all the experiments. A single line was used to determine the lateral wetting width. The width : depth ratios for the three soil types and three emitter discharge rates were used to compare the measured width : depth ratios with the standard 0.8 value recommended in South Africa for design purposes. The ratios for all three soil types were higher than 0.8 and it increased with an increase in the silt plus clay percentage. It is possible that the emitter spacing of 60 cm was too small. When the emitters are spaced too close a wet line develop below the lateral which enhance sideward water distribution. It is possible that wider inline emitter spacings might effect the width : depth ratio. This hypothesis can be the objective of another investigation.

A proposal for emitter spacing was obtained by multiplying the measured width : depth ratio by 0.8 to give the emitter spacing factor. When the required depth of wettingwhich is determined by either soil or rooting depth, is known, the inline emitter spacing can be calculated by multiplying the required wetting depth by the emitter spacing factor. The recommended emitter spacing factors can be used to determine the inline emitter spacing on soils with a high fine sand fraction, and without stones:

- Non-luvic fine sand 0.88
- Luvic fine sand 1.28
- Sandy clay loam 2.56

The effect of applying these recommended factors, on inline emitter spacing is illustrated in Table 4.2, for different required wetting depths.

Pedotransfer functions that can be used to estimate the width : depth ratio of the potential wetted soil below an emitter, from the mean silt plus clay percentage of the soil, was developed. These functions are actually only applicable where the inline spacing is 60 cm or less. It is essential that similar functions should be derived, or these be tested, at inline emitter spacings greater than 60 cm.

A single line with a constant inline emitter spacing of 60 cm was used to determine the lateral wetting width. Pedotransfer functions were derived that can be used to estimate the wetting depth after 20 mm irrigation was applied on a wet soil followed by redistribution, from the mean silt plus clay percentage of the wetted soil volume. These functions were used to estimate the wetting depth for different silt plus clay contents, increasing with 2% intervals. Guidelines that can be used to estimate the maximum lateral spacing for a soil from the mean silt plus clay percentage of the potential wetting volume, were suggested for different emitter discharge rates. The estimated width : depth ratio was calculated from the silt plus clay percentage using pedotransfer functions derived for this purpose. The proposed maximum spacing was calculated by multiplying the estimated wetting width by 0.9 to create a 10% overlap and continuous wetting area. It should be emphasized that these suggested guidelines will only be applicable to soils where fine sand dominates the sand fraction.

The third objective of the study was to quantify the movement of nitrate applied through the emitters, on one soil type and emitter discharge rate. The distribution patterns of nitrate, was investigated on a luvic fine sand with an emitter discharge rate of 2 l h^{-1}. The nitrate distribution patterns were determine around a single line of emitters with design characteristics similar to the water distribution measurements. The study consisted of two experiments. During the first experiment, the nitrate was applied during the first 50 minutes (2.2 mm) of a 20 mm irrigation event on a dry soil. Three days was allowed for redistribution before the first samples were taken at the same distances and depths from the emitter as for the water distribution measurements using a soil auger. On the fourth day another 20 mm irrigation was applied, after three days redistribution, the last samples were taken. During the second experiment, the nitrate was applied during the last 2.2 mm (50 minutes) of an irrigation event of 20 mm. On the fourth day, another 20 mm irrigation was applied. Sampling for nitrate distribution was the same as for the first experiment. The nitrate concentration in the irrigation water was 4.35 g NO_3^- l^{-1} which represents a 1/5 of a total seasonal application of 220 kg N ha^{-1} or 44 kg N ha^{-1}. Calsium nitrate was used as a N-source. Nitrate in a CaCl soil extract was determined with the salisilate method. The increase in the nitrate content of the soil, expressed in mg NO_3^- kg^{-1} soil at each of the sampling positions were obtained by subtracting the readings before from the readings after application.

When nitrate was applied at the beginning of an irrigation event the distribution pattern was much more even throughout the profile with more lateral movement than when applied at the end of an irrigation event. When an additional 20 mm irrigation was added on the treatment, where NO_3^- was applied in the beginning, pockets of nitrate formed in the top 20 cm of the profile, 20-60 cm away from the emitter. The application of nitrate in the beginning of an irrigation event is recommended where a single emitter supply nitrate to more than one plant for example, for crops that is spaced close together or where the emitters are placed between two crop rows.

When the nitrate was applied at the end of the irrigation event, the largest portion of the nitrate remained below the emitter and little lateral movement occurred. When an additional 20 mm irrigation was applied, the majority of the nitrate moved downward with some lateral movement. Therefore application of nitrate at the end of an irrigation event is recommended where more than one emitter is used to apply nitrate to a single plant for example, trees.

Further research opportunities

This research was done on soils with predominantly fine sand in the sand fraction, with a fixed inline emitter spacing of 60 cm. The method of determining the wetting front worked very well and can be used in future studies. To create more possibilities for the prediction of wetting patterns on various soil types, it is suggested that the following aspects need further research:

1. Measuring of wetting patterns for soils containing more coarse sand in the sand fraction and in stony soils.
2. Measuring of wetting patterns below one emitter will make predictions for inline emitter spacing a lot easier. The effect of inline emitter spacing on the width : depth ratio of the wetting pattern need to be investigated on different soil types before the larger ratios, derived in this study, can be used with confidence for calculating the inline emitter spacing.
3. Measuring of fertigated nitrate distribution patterns on other soil types especially on non-luvic sandy and more clayey soils.
4. Measuring of wetting patterns in fields with actively growing crops.

5. Evaluating water to air distribution within wetting patterns for different discharge rates and soil types on actively growing crops.
6. Measuring distribution patterns for other fertigated nutrients.

ABSTRACT

Field trails were conducted in the Free State to quantify the affect of soil hydraulic properties on the dimensions of the wetted volume below trickle irrigation emitters. Three different soil types, a non-luvic fine sand (6-17% silt plus clay), luvic fine sand (9.5-20.75% silt plus clay) and sandy clay loam (26.5-39.75% silt + clay)) and three emitter discharge rates 1.2, 2 and 8 l h^{-1} were used to determine the water distribution pattern below trickle emitters. The water content, expressed in mm water per 100 mm soil depth, was measured with a neutron probe at 10 cm depth intervals till a depth of 155 cm, for each access tube 5, 25, 45, 65, 85, 105, 125 and 145 cm away from the emitter and between two emitters. The wetting patterns were presented in diagrams, indicating the increase in water content in each cell as shades of blue.

Soil texture and emitter discharge rate played an important role in the distribution of water below trickle emitters. The most acceptable way to quantify the wetted area was the ratio between the width and depth of the wetting front. The width : depth ratio of the wetted volume emphasizes the shape of the distribution pattern. It was found that this ratio increased with an increase in the average silt plus clay percentage of the wetted soil, for all the emitter discharge rates. This effect of texture was more pronounce for emitters with a discharge rate of 2 l h^{-1} and higher.

The effect of emitter discharge rate on the width : depth ratio was different for the three soil types. For both the luvic fine sand and sandy clay loam, irrespective of initial wetness, the width : depth ratio increased sharply from the 1.2 l h^{-1} to the 2 l h^{-1} emitter rates after which it remained the same to 8 l h^{-1} emitters. On the non-luvic fine sand emitter discharge rate had little effect on the width : depth ratio. Practically, higher emitter rates is preferable on sandy soils and lower emitter rates for both the luvic fine sands and sandy clay loams.

Because the design criteria for trickle irrigation systems in South Africa presently does not take the physical and hydraulic soil properties into account when designing trickle irrigation systems, present guidelines used in South Africa were evaluated by using important properties like soil texture, which came forward in the study. The width to depth ratio of not less than 0.8 which is currently used in South Africa was compared with actual measured data from the study. The measured width : depth ratios for all three soil types were higher than 0.8 and it increased with an increase in the silt plus clay percentage. It was difficult to set guidelines because a fixed inline emitter spacing of 60 cm was used throughout the study which caused wetting volumes to overlap, especially on soils with a high silt plus clay content. This overlapping could influence the width to depth ratio. A proposal for emitter spacing was obtained by multiplying the measured width : depth ratio by 0.8 to give the emitter spacing factor. Thus, when the required depth of wetting which is affected by rooting and soil depths, is known, the inline emitter spacing can be calculated by multiplying the wetting depth by the emitter spacing factor. The following emitter spacing factors could be used to determine the inline emitter spacing of the experimental soils: non-luvic fine sand (0.88), luvic fine sand (1.28) and sandy clay loam (2.56).

A single line with a constant inline emitter spacing of 60 cm was used to determine the lateral wetting width. Pedotransfer functions, relating the wetting depth after 20 mm irrigation was applied on a wet soil to the mean silt plus clay percentage of the wetted soil volume, were derived. These functions were used to estimate the wetting depth for different silt plus clay contents, increasing with 2% intervals. Guidelines that can be used to estimate the maximum lateral spacing for a soil, from the mean silt plus clay percentage of the potential wetting volume, were derived for different emitter discharge rates. These guidelines are proposed for soils with predominantly fine sand in the sand fraction.

In a second field trail the effect of timing of nitrate application through trickle irrigation on the NO_3^--distribution through the profile was detected. This experiment was done on a luvic fine sand with an emitter discharge rate of 2 $l\ h^{-1}$. This experiment consisted of two treatments. For the first treatment, the nitrate was applied in the beginning of a 20 mm irrigation event on a dry soil. After 4 days an additional 20 mm irrigation was applied. Nitrates moved away from the emitter and pockets of nitrate formed in the topsoil 30 cm away from the emitter. The nitrate distribution pattern stayed the same after an additional 20 mm irrigation. Nitrate spread laterally more evenly throughout the profile, with a wider and deeper distribution than when applied at the beginning of the irrigation event. The application of nitrate in the beginning of an irrigation is ideal where a single emitter supply nitrate to more than on plant for example, for crops that is spaced close together or where the emitter lines is laid between two crop rows. During a second treatment, nitrate was applied at the end of the irrigation event which was followed up by an additional 20 mm irrigation, four days later. The highest concentration nitrate stayed right below the emitter with some lateral movement. Most of the nitrates moved with the water when an additional 20 mm water was applied with small pockets of nitrate forming in the topsoil, 40 cm from the emitter. The application of nitrate at the end of an irrigation is ideal where more than one emitter is used to apply nitrate to a single plant for example, tree crops.

Keywords: Soil texture, emitter discharge rate, width to depth ratio, inline emitter spacing, lateral spacing, nitrate distribution

OPSOMMING

Verskillende veldproewe is uitgevoer in die Vrystaat om die effek van grond hidrouliese eienskappe en drupperleweringstempo op die afmetings van die benatte volume onder drupbesproeiing te bepaal. Drie verskillende grond tipes, 'n nie-luviese fynsand (6-17% slik plus klei), 'n luviese fynsand (9.5-20.75% slik plus klei) en 'n sandkleileem (26.5-39.75% slik plus klei) en drie verskillende drupperlewerings 1.2, 2 en 8 *l* uur^{-1} is gebruik om die water verspreidingspatrone onder druppers te bepaal. Die waterinhoud, uitgedruk in mm water per 100 mm diepte, is gemeet met 'n neutronmeter vir elke 10 cm interval in die onderskeie toegangsbuise, 5, 25, 45, 65, 85, 105, 125 en 145 cm weg van die drupper en tussen twee druppers. Die benattingspatrone is voorgestel in diagramme wat die toename in waterinhoud in elke sel voorstel, in skakerings van blou.

Grondtekstuur en drupperlewering het albei 'n belangrike rol gespeel in die verspreiding van water onder druppers. Die mees aanvaarbare manier om die benatte area te beskryf was met die verhouding tussen die wydte en diepte van die benattingsfront. Die breedte- tot diepte-verhouding van die benatte volume beskryf die vorm van die verspreidingspatroon. Daar is gevind dat hierdie verhouding toeneem met 'n toename in die gemiddelde slik plus klei persentasie van die benatte grond, by al die drupperleweringstempo's. Die effek van grondtekstuur was meer prominent vir druppers met 'n leweringstempo van 2 *l* uur^{-1} en hoër.

Die effek van drupperlewering op die breedte- tot diepte-verhouding van die benatte sone was verskillend vir die verskillende grondtipes. Vir beide die luviese fynsand en sandkleileem, ongeag van oorspronklike natheid, het die breedte- tot diepte-verhouding skerp toegeneem vanaf die 1.2 *l* uur^{-1} tot die 2 *l* uur^{-1} drupperleweringstempo's waarna dit dieselfde gebly het tot die 8 *l* uur^{-1} drupper. Op die nie-luviese fynsand het drupperlewering slegs 'n geringe invloed op die breedte- tot diepte-verhouding gehad. Vir praktiese toepassing word drupperleweringstempo's hoër as 2 *l* uur^{-1} aanbeveel vir sanderige gronde en laer drupperleweringstempo's vir beide luviese fynsande en sandkleileem gronde.

Omdat die huidige riglyne vir die ontwerp van drupbesproeiingstelsels nie grondfisiese en -hidrouliese eienskappe in aanmerking neem nie, is die huidige riglyne wat in Suid Afrika gebruik word ge-evalueer deur belangrike eienskappe soos grondtekstuur, wat in die studie uitgekom het, as veranderlikes voor te stel. Die huidige voorgestelde breedte- tot diepte-verhouding van minstens 0.8 is vergelyk met die werklike data wat met die studie verkry is. Die gemete breedte- tot diepte-verhouding vir al drie grondsoorte was hoër as 0.8 en het met 'n toename in die slik plus klei-persentasie toegeneem. Omdat daar deurgaans met 'n vaste inlyn drupperspasiëring van 60 cm gewerk is, was dit moeilik om aanvaarbare riglyne voor te stel aangesien die benattingsvolumes oorvleuel het, veral in gronde met hoë slik plus klei-inhoud. Die breedte- tot diepte-verhouding kan hierdeur beïnvloed word. 'n Voorstelling vir drupperspasiëring is opgestel deur die werklike gemete breedte- tot diepte-verhoudings met 0.8 te vermenigvuldig om die drupperspasiëringsfaktor te gee. Die verlangde benattingsdiepte van 'n grond word deur die grond- of potensiële bewortelingsdiepte bepaal, watter ookal die vlakste is. Dus, as die verlangde diepte van benatting bekend is, kan die inlyn drupperspasiëring bereken word deur die benattingsdiepte met die drupperspasiëringsfaktor te vermenigvuldig. Die volgende drupperspasiëringsfaktore kan gebruik word om die inlyn drupperspasiëring van die eksperimentele gronde te bepaal: nie-luviese fynsand (0.88), luviese fynsand (1.28) en sandkleileem (2.56).

'n Enkel lyn met 'n konstante inlyn drupperspasiëring van 60 cm is gebruik om die laterale benattingsbreedte, te bepaal. Pedo-oordragingsfunksies is afgelei wat gebruik kan word om die benattingsdiepte na 20 mm besproeiing op 'n nat grond, vanaf die gemiddelde slik plus klei persentasie van die benatte grondvolume, te beraam. Hierdie funksies is gebruik om die benattingsdiepte vir elke 2% toename in slik plus kleiinhoud te beraam. Riglyne wat gebruik kan word om die maksimum laterale spasiëring vanaf 'n grondsoort se gemiddelde slik plus klei persentasie te beraam, is afgelei vir verskillende drupperleweringstempo's. Die riglyne kan gebruik word op gronde waar die dominante sandfraksie, fynsand is.

In 'n tweede veldproef is ondersoek ingestel of die tyd van nitraattoediening deur drupbesproeiing enige effek op die verspreiding daarvan deur die grondprofiel het. Hierdie proef is op die luviese fynsand met 'n drupper leweringstempo van 2 *l* uur^{-1}, uitgevoer. Die proef het uit twee behandelings bestaan. Tydens die eerste behandeling is die nitrate aan die begin van die besproeiing op 'n droë grond toegedien waarna 'n opvolg 20 mm besproeiing vier dae daarna toegedien is. Die nitrate het weg beweeg vanaf die drupper en pakkies nitraat in die bogrond ongeveer 30 cm vanaf die drupper gevorm. Die nitraatverspreidingspatroon het dieselfde gebly na die opvolg besproeiing. Nitrate het meer egalig lateraal en dieper versprei wanneer dit aan die begin van die besproeiingsgebeurtenis toegedien is. Toediening van nitraat aan die begin van 'n besproeiing is ideal waar 'n enkel drupper nitraat aan meer as een plant voorsien byvoorbeeld, vir gewasse wat naby aan mekaar gespasiëer is of waar die drupperlyn tussen twee gewasrye gelê word. Tydens die tweede behandeling is nitrate aan die einde van die besproeiingsgebeurtenis toegedien waarna 'n opvolg 20 mm besproeiing vier dae later toegedien is. Die hoogste konsentrasie nitrate het reg onder die drupper gebly met net 'n bietjie laterale verspreiding. Na die opvolg 20 mm besproeiing het die grootste gedeelte nitrate saam met die water afbeweeg en klein pakkies nitraat het in die bogrond gevorm, 40 cm vanaf die drupper. Toediening van nitrate aan die einde van 'n besproeiing is ideal waar meer as een drupper nitraat aan 'n enkel plant voorsien byvoorbeeld, boomgewasse.

Sleutelwoorde: Grondtekstuur, drupperleweringstempo, breedte- tot diepte-verhouding, inlyn drupperspasiëring, laterale spasiëring, nitraatverspreidinspatroon

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APPENDIX

Appendix 3.2 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 1.2 l h^{-1} emitter rate on a non-luvic fine sand

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance	Depth	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
from emitter	(cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	5.77	6.27	14.95	12.96	10.99	10.75	7.17	7.86	13.22	11.59	8.7	8.13
5	15	10.21	10.41	20.08	18.99	16.24	16.44	11.73	12.5	18.16	17.03	13.33	12.4
5	25	11.96	12.2	20.19	19.37	17.61	18.13	13.57	14.29	18.56	18.13	15.18	14.63
5	35	13.48	13.35	20.63	19.87	19.4	19.04	15.59	16.1	18.39	18.75	16.46	16.34
5	45	15.93	16.23	22	19.97	21.34	21.19	18.86	18.52	19.92	20.14	18.94	18.98
5	55	17.61	17.62	20.95	18.66	23.13	22.85	20.5	20.25	20.97	20.48	20.53	20.54
5	65	16.83	16.85	18.27	16.06	23.45	22.67	21.15	20.69	21.44	20.96	21.04	21.62
5	75	14.48	14.13	14.41	13.24	22.32	21.44	21.27	20.56	20.81	20.63	20.3	21.41
5	85	12.68	12.25	12.76	12.17	20.12	18.81	20.86	19.97			20.33	20.91
5	95	12.26	12.08	12.18	11.56	16.7	14.82	19.88	19.37			19.29	20.23
5	105	11.79	11.53			13.1	12.09	19.2	18.18			18.4	19.14
5	115	10.9	11.29			11.33	10.82	16.96	16.04			17.87	18.02
5	125	10.75	11.01					14.58	13.33			16.25	16.85
5	135	10.98	11					11.83	11.19			14.94	15.61
5	145	11.26	10.9					11.4	11.18			13.22	13.94
5	155	12.02	11.92					11.93	11.92			12.07	12.75
25	5	5.63	6.12	7.56	8.47	7.12	8.45	6.17	7.2	7.02	8.35	7.82	6.32
25	15	11.06	11.31	14.38	15.45	13.8	15.28	12.08	12.95	13.82	15.38	13.6	12.43
25	25	13.79	13.98	17.08	17.08	17.36	17.86	15	15.38	16.85	17.3	16.32	15.53
25	35	15.75	15.73	19.26	18.28	19.61	20.1	17.37	17.19	18.58	18.69	17.63	17.49
25	45	18.08	18.15	20.73	20.29	22.6	22.22	20.02	20.47	20.72	20.71	20.59	20.54
25	55	19.35	19.66	21.44	20.34	23.67	23.04	21.82	21.37	21.66	21.29	21.12	21.7
25	65	18.88	18.87	19.63	18.41	22.98	22.6	21.83	21.18	21.46	20.98	21.34	21.48
25	75	16.68	16.26	17.07	16.34	21.79	21.02	20.39	20.3			20.4	20.81
25	85	14.06	13.66	14.44	13.66	19.24	18.43	20.09	19.14			19.7	19.98
25	95	12.45	12.47	12.37	12.11	15.62	14.01	19.43	18.25			18.73	19.58
25	105	11.63	11.66			12.66	11.74	18.07	17.31			18.09	18.87
25	115	11.28	11.34			11.13	10.84	16.67	15.34			17.23	17.51
25	125	10.82	10.92					13.63	13.13			16.15	16.72

Appendix 3.2 (continue)

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
25	135	11.07	11.06					11.56	11.31			15.51	15.28
25	145	11.25	11.39					11.41	11.68			13.09	13.42
25	155							12.12	12.16			12.37	12.49
45	5	6.37	7.78	6.48	8.26	6.39	8.51	6.19	7.69	6.07	7.78	7.95	6.2
45	15	11.89	13.03	12.2	13.14	12.59	14.67	11.73	13.31	11.78	13.16	13.28	12.03
45	25	15.09	15.35	14.96	15.49	16.13	16.76	15.07	15.78	14.91	15.94	15.92	15.02
45	35	17.17	17.75	17.13	17.22	19.14	19.24	17.71	17.92	17.57	17.67	18.09	17.53
45	45	19.46	19.9	19.19	19.68	21.11	21.34	19.78	20.65	19.89	20.34	20.29	20.15
45	55	20.23	20.05			21.53	21.62	21.01	20.84	21.16	20.68	20.98	20.94
45	65	19.78	19.7			21.29	21.23	20.52	20.63	20.59	20.44	21	20.68
45	75	18.48	18.71			19.79	20.33	20.17	20.41			20.72	19.87
45	85	16.54	17.09			18.07	17.65	19.39	19.46			20.36	19.5
45	95	14.15	14.23			15.85	15.46	18.27	18.56			19.09	18.78
45	105	12.51	12.5			13.19	13.19	16.48	16.5			17.49	17.79
45	115	11.48	11.55			11.8	11.67	14.33	13.3			15.82	16.48
45	125	10.79	11.06			10.74	11.39	11.76	11.67			14.58	15-Jan
45	135	11.28	11.36					11.24	11.13			12.81	13.43
45	145	11.57	11.66									12.06	12.25
45	155	12.43	12.4									12.54	12.26
65	5	5	7.19			4.73	7.41	4.71	6.99			7.06	4.55
65	15	10.01	11.4			9.87	11.37	9.58	11.07			11.11	9.28
65	25	12.82	13.46			12.76	14.18	12.81	14.21			13.78	12.38
65	35	16.07	16.87			15.69	16.84	16.04	16.82			16.99	15.89
65	45	19.37	19.81			19.67	19.88	19.28	19.84			19.96	19.3
65	55	20.25	19.89			20.63	19.86	20.18	20.29			20.14	20.61
65	65	19.65	19.85			19.99	19.61	20.08	20.1			20	20.12
65	75	19.56	19.26			19.47	19.57	19.97	20.12			19.76	19.77
65	85	18.96	18.59					19.42	19.48			19.58	19.41
65	95	17.38	17.07					18.57	18.33			18.46	18.32

Appendix 3.2 (continue)

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
65	105	15	14.35					16.64	16.01			17.04	17.32
65	115	12.29	12.31					13.89	13.85			15.65	15.53
65	125	11.31	11.47					11.94	12.16			13.75	13.51
65	135	10.93	11.58					11.23	11.63			12.31	12.12
65	145	11.47	11.86					11.19	11.7			11.86	11.71
65	155	12.12	12.67									12.71	11.92

Appendix 3.3 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 2 l h^{-1} emitter rate on a non-luvic fine sand

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance	Depth	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
from emitter	(cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	8.31	9.1	20.55	19.88	21.13	20.12	12.23	12.26	20.06	20.58	11.93	12.28
5	15	12.37	12.9	22.57	21.95	22.95	22.77	15.46	15.73	22.45	22.6	15.48	15.79
5	25	14.41	15.33	22.76	23.09	23.84	24.06	17.54	18.55	23.09	23.41	17.28	18.6
5	35	16.12	16.61	22.14	22.42	24.1	24.23	19.33	20.04	23.34	24.02	19.03	19.73
5	45	15.99	16.76	19.01	18.27	24.48	24.82	19.45	20.27	22.67	23.02	19.64	20.3
5	55	14.64	15.76	15.3	15.86	23.56	23.89	20.11	20.2	21.2	21.91	19.38	20.21
5	65	13.18	14.21	13.36	14.07	23.03	22.73	20.31	20.47	20.36	20.82	19.79	20.52
5	75	11.77	12.21	11.92	12.53	19.87	20.29	20.28	20.44	20.19	20.7	20.6	20.89
5	85	11.52	11.83	11.44	11.99	14.96	15.04	20.7	21.03			20.41	20.65
5	95	11.87	11.92			12.15	12.21	19.84	20.04			20.27	20.42
5	105	11.68	11.38			11.49	11.66	19.41	19.24			20.17	19.86
5	115	11.41	11					18.04	17.86			19.46	19.6
5	125	11.35	10.99					15.74	16.08			18.96	19.01
5	135	11.26	10.78					13.18	13.59			17.94	17.89
5	145	11.21	11.06					12.11	11.8			17.11	17.18
5	155	11.62	11.67					11.72	11.71			14.6	15.79
5	165	12.25	12.17					12.13	12.2			13.1	13.83
5	175	12.86	13.02					13.07	13.01			13.2	13.43
5	185	13.79	13.53									13.84	13.76

Appendix 3.3 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07		
Distance	Depth	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)		
from emitter	(cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	
25	5	5.68	7.1	13.71	13.94	14	15.29	8.04	9.6	14.12	16.41	8.21	9.65	
25	15	9.82	10.38	17.43	16.34	18.1	18.53	12.4	13.21	18.53	19.32	12.6	13.12	
25	25	12.51	12.37	17.88	15.49	19.75	20.59	15.25	15.31	19.67	20.34	14.91	15.1	
25	35	13.75	13.78	16.51	15.06	21.43	20.84	16.87	16.44	20.2	20.18	16.69	16.89	
25	45	14.17	14.74	14.71	14.74	21.51	22.04	17.87	18.4	19.52	20.62	17.81	18.58	
25	55	13.43	14.05	13.39	14.01	20.87	21.84	18.58	19.53	19.27	20.26	18.76	19.34	
25	65	12.12	12.62	11.94	12.51	17.94	19.45	18.81	20.17	18.87	19.85	19.02	20.04	
25	75	11.46	11.63	11.15	12.1	13.47	14.51	18.86	20.04	19.08	19.89	19.13	19.95	
25	85	11.33	11.93	11.36	11.95	11.84	12.23	18.77	20			19.44	20.42	
25	95	11.56	11.53			11.59	11.53	18.67	18.67			18.83	20.05	
25	105	11.16	11.5			11.19	11.36	17.26	17.8			18.62	19.18	
25	115	10.91	10.59					15.65	16.03			18.32	18.27	
25	125	10.51	10.34					13.29	13.55			17.41	17.59	
25	135	10.76	10.68					11.64	11.32			16.46	16.78	
25	145	11.17	11.09					11.18	10.99			15.37	16.12	
25	155	11.48	11.63					11.62	11.31			13.46	14.23	
25	165	12.34	12.11					12.31	12.27			12.64	12.99	
25	175	13.36	12.87									13.29	12.95	
45	5	6.88	8.33	7.73	8.88	8.9	11.03	8.35	10	9.03	11.39	8.5	10.19	
45	15	11.34	12.13	11.79	12.55	14.37	15.63	12.95	14.04	14.01	15.35	13.15	14.21	
45	25	14.47	14.89	14.61	14.99	17.1	17.73	16.51	18	17.2	18.04	16.6	17.15	
45	35	15.59	15.35	15.91	15.78	18.85	18.25	18.41	18.18	18.49	18.62	18.25	18.41	
45	45	15.34	15.03	15.61	15.26	17.35	16.71	18.74	17.98	18.5	18.46	18.86	18.7	
45	55	14.25	13.73	13.98	13.8	15.14	14.83	18.04	17.29	17.83	17.76	18.73	18.39	
45	65	12.45	12.15	12.5	12.1	12.83	12.5	17.12	16.96	17.09	17.38	18.04	18.27	
45	75	11.47	11.71	11.67	11.52	11.71	11.5	16.4	16.54	16.5	17.38	17.75	18.36	
45	85	11.38	11.37	11.83	11.74	11.29	11.51	15.61	15.44			17.61	18.36	
45	95	11.28	11.53			11.55	11.53	13.59	13.07			17.34	18.19	
45	105	10.79	11.06			11.28	11.04	12.42	12.83			16.48	16.57	
45	115	10.43	10.69					11.23	12.83			15.1	15.63	
45	125	10.5	10.22					10.38	11.33			13.95	14.37	
45	135	10.6	10.69					10.63	10.77			12.53	13.13	
45	145	11.03	10.81					11.15	11.06			11.58	45	155

Appendix 3.3 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
65	5	6.4	7.47			6.63	7.45	6.61	7.55	7.18	7.74	6.86	7.93
65	15	11.61	12.05			11.79	12.22	11.6	12.49	12.21	12.42	11.92	12.54
65	25	14.48	14.87			14.6	15	15.26	15.3	14.92	15.4	15.17	15.51
65	35	16.13	16.15			15.92	15.86	16.46	16.54	16.79	16.61	17.02	16.74
65	45	15.86	15.71			15.61	15.7	16.82	16.32	16.46	16.35	16.87	16.95
65	55	14.67	14.82			14.89	14.74	15.76	15.73	15.89	15.77	16.58	16.47
65	65	13.07	13.18			12.7	13.17	13.98	14	13.88	14.29	15.31	15.63
65	75	11.91	12.03			11.89	11.8	12.45	12.48	12.42	12.53	14.13	14.58
65	85	11.29	11.65			11.58	11.64	11.73	11.89			13.35	13.17
65	95	11.5	11.65			11.29	11.49	11.72	11.38			12.61	12.73
65	105	11.04	11.35			10.99	10.94	11.07	10.98			12.04	12.16
65	115	10.86	10.72					10.73	10.7			10.99	10.7
65	125	10.62	9.55					10.48	10.05			10.81	10.07
65	135	10.76	10.13					10.79	9.67			10.62	10.01
85	5	6.1	7.38									5.94	7.21
85	15	10.45	11.64									10.28	11.17
85	25	13.42	13.84									13.3	14
85	35	15.59	15.27									15.54	15.44
85	45	15.51	15.72									16.16	15.79
85	55	15.19	14.6									15.05	14.98
85	65	13.39	12.37									13.89	13.14
85	75	12.02	11.28									12.42	11.9
85	85	11.49	11.16									11.82	11.41
85	95	11.57	10.79									11.4	11.33
85	105	11.17	10.66									11.03	10.67
85	115	10.79	10.23									11	10.51
85	125	10.76	10.26									10.61	10.08

Appendix 3.4 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 8 l h^{-1} emitter rate on a non-luvic fine sand

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	7.69	5.38	23.86	20.23	24.26	18.86	11.26	7.85	20.99	16.05	11.05	7.87
5	15	10.77	9.57	23.98	24.91	24.46	24.32	14.1	12.71	22.74	22.26	14.1	12.95
5	25	13.33	12.68	21.47	23.91	24.49	24.31	16.66	16.15	22.28	22.95	16.93	16.12
5	35	14.82	15.04	17.31	20.44	24.51	25.78	18.26	18.54	21.11	22.55	18.56	18.25
5	45	15.08	15.95	15.45	17.2	24.91	26.06	19.11	19.95	19.82	21.8	19.24	19.63
5	55	14.91	16.03	15.14	15.92	23.55	26.01	19.54	20.19	19.7	20.76	19.56	20.45
5	65	14.58	15.02	14.6	14.96	19.41	24.79	20.12	20.69	20.07	20.62	20.23	20.72
5	75	12.87	13.54			14.12	19.8	20.51	21.09			20.3	21.13
5	85	11.7	12.34			11.68	13.6	20.23	22.14			20.16	21.77
5	95	11.15	11.51			11.15	11.81	19.86	21.48			20.01	21.58
5	105	10.82	11.14					18.26	20.78			19.38	20.74
5	115	10.61	10.68					17.41	19.54			18.78	20.09
5	125	10.25	10.58					16.19	18.8			17.89	19.07
5	135	10.56	10.42					14.19	17.55			17.67	19.08
5	145	11.16	10.89					11.94	15.21			17.52	18.66
5	155	11.65	11.32					12.04	13.13			15.97	18.01
5	165	12.51	12.18					12.58	12.53			13.98	16.98
5	175	13.23	13.07									13.48	14.96
5	185	13.45	13.89									13.87	14.63
5	195	14	14.58									14.35	14.92
25	5	6.07	3.62	18.88	12.24	19.44	11.62	8.55	4.84	16.68	9.11	8.44	4.48
25	15	9.04	7.58	21.05	20.23	22.87	20.68	12.3	10.05	19.48	16.82	11.93	9.99
25	25	11.73	9.98	18.55	20.9	23.9	23.06	14.34	12.87	18.39	18.13	14.41	12.99
25	35	12.93	11.67	15.49	18.15	24.91	24.17	15.97	14.58	17.6	17.15	16.3	14.5
25	45	14.07	12.71	14.17	15.33	25.14	24.71	17.87	16.31	17.79	16.94	17.92	16.51
25	55	14.4	13.63	14.23	14.05	22.56	24.96	18.48	17.89	18.95	17.99	19.04	17.79
25	65	13.03	13.55			17.75	23.93	19.46	18.93	19.29	18.68	19.53	18.89
25	75	11.84	11.85			12.66	18.93	20	19.11			19.73	19.01
25	85	11.23	11.35			11.24	12.75	19.27	19.54			19.59	19.36
25	95	10.84	11.31			11.41	11.59	18.97	19.91			19.15	19.51

Appendix 3.4 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
25	105	10.79	11.2					18.1	19.35			18.58	19.65
25	115	10.65	10.79					16.62	18.57			18.29	19.14
25	125	10.39	10.42					14.97	17.44			17.72	18.46
25	135	10.59	10.27					12.8	16.25			17.13	17.93
25	145	11.19	10.88					11.59	14.28			16.49	17.63
25	155	11.81	11.45					11.87	12.23			14.93	17.47
25	165	12.51	12.05					12.52	12.43			13.76	16.51
25	175	13.29	13.26									13.6	15.06
25	185	14.02	13.87									13.87	13.98
45	5	6.13	5.83	7.59	6.52	10.75	9.53	8.21	6.95	9.29	7.15	8.3	6.91
45	15	9.71	9.77	11.03	11.35	16.19	16.08	12.53	12.29	13.53	12.63	12.47	12.23
45	25	12.49	12.15	13	12.89	18.98	20.06	15.51	15.03	15.63	15.48	15.41	14.93
45	35	14.74	14.16	14.79	14.74	20.86	22.52	17.61	17.66	18.04	18.18	17.6	17.75
45	45	15.59	15.55	15.57	15.77	21.35	23.53	19.32	19.45	18.76	19.68	18.62	20.01
45	55	15.2	15.7	15.06	15.28	17.82	23.18	19.24	20.64	18.84	20.35	18.8	20.38
45	65	13.49	14.42	13.48	13.99	14.2	18.4	19.05	20.35	18.76	20.53	19	20.39
45	75	11.57	12.3	11.82	12.4	11.81	13.55	18.68	21.04			18.85	20.92
45	85	11.36	11.93	11.32	11.9	11.36	12.12	18.2	20.37			18.82	20.65
45	95	11.22	11.7			11.31	11.81	16.85	20.08			18.15	20.25
45	105	10.81	11.67					15.71	19.19			17.1	19.69
45	115	10.64	11.11					13.16	17.67			16.53	18.83
45	125	10.92	10.72					11.32	15.85			16.07	17.75
45	135	10.69	10.71					10.91	13.75			14.69	17.3
45	145	11.19	11.43					11.16	11.97			12.82	16.75
45	155	11.95	11.53					11.91	11.87			12.46	15.61
45	165	12.82	12.39									12.77	14.49

Appendix 3.4 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
65	5	6.19	5.69	6.73	5.81	6.37	6.16	6.89	6.54			6.74	6.22
65	15	10.35	10.31	10.44	10.55	10.54	10.57	11.14	11.21			11.27	10.79
65	25	13.41	13.22	13.37	13	13.71	13.53	14.3	14.47			15.04	14.62
65	35	15.4	15.83	15.51	15.64	16.05	16.1	17.1	17.88			17.55	18.11
65	45	16.53	16.8	15.96	16.94	15.77	16.84	18.38	19			18.35	19.02
65	55	16	15.46	15.49	15.82	15.52	16	18.02	18.21			18.15	19.03
65	65	13.57	13.98	13.85	13.98	13.89	14.14	17.31	17.84			17.88	17.78
65	75	12.22	12.3	12.03	12.24	12.01	12.19	15.57	16.82			17.25	17.71
65	85	11.63	11.52	11.71	11.35	11.47	11.67	14.47	15.58			17.09	17.45
65	95	11.58	11.39			11.2	11.45	12.78	14.91			16.04	16.9
65	105	11.03	11.35					11.64	13.44			14.44	16.49
65	115	10.98	11.02					11.24	11.89			12.77	15.2
65	125	10.99	10.72					10.57	10.9			11.56	13.31
65	135	10.97	10.63					11.1	10.84			11.23	12.34
65	145	11.35	11.09					11.11	11.25			11.41	11.88
65	155	11.72	11.74					12.25	11.9			12.19	12.16
65	165	12.7	12.66									12.67	12.76
85	5	5.48	5.11			5.45	5.16	5.65	4.77			5.61	4.68
85	15	9.32	9.37			9.53	9.75	9.6	9.39			9.67	9.48
85	25	12.21	11.9			12.25	11.97	12.44	12.41			12.77	12.38
85	35	14.89	15.15			15.08	14.94	15.39	15.71			16.12	16.19
85	45	15.69	17			15.93	16.87	16.79	18.07			17.21	18.13
85	55	15.44	16.31			15.89	16.66	16.17	16.93			16.85	18.08
85	65	14.11	14.29			14.12	14.44	14.75	15.57			15.89	16.39
85	75	11.95	12.19			12.17	12.43	12.65	12.92			13.59	14.69
85	85	11.32	11.92			11.42	11.86	11.48	11.83			11.98	13.03
85	95	11.41	11.61			11.47	11.57	11.38	11.87			11.78	12.48

Appendix 3.4 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
85	105	11.03	11.51					10.95	11.41			11.56	11.73
85	115	11.08	10.99					10.75	11.01			11.08	11.19
85	125	11.03	10.89					10.84	10.95			10.93	11.25
85	135	11.05	10.92					10.91	11.01			10.93	11.22
85	145	10.93	11.33					11.13	11.38			11.29	11.1
85	155	11.78	12.03									11.6	11.79
105	5	5.51	4.84					5.7	4.63			5.51	4.61
105	15	9.79	9.39					9.88	9.23			9.99	9.16
105	25	13.43	12.98					13.13	12.65			13.57	12.95
105	35	15.91	15.42					15.99	15.6			15.98	16
105	45	17.21	17.3					17.46	17.92			17.27	17.9
105	55	16.65	16.58					16.8	17.18			17.18	17.06
105	65	15.1	15					15.29	15.01			15.65	15.29
105	75	13.31	12.5					13.5	12.78			13.97	13.52
105	85	12.5	11.62					12.58	12.27			12.65	11.81
105	95	12.36	11.71					12.49	11.97			12.46	11.87
105	105	11.93	11.85					11.98	11.65			12.23	11.73
105	115	11.71	11.53									11.58	11.71
125	5	4.94	5.15					5.99	5.46				
125	15	9.63	10.02					9.84	10.08				
125	25	13.25	13.66					13.78	13.79				
125	35	16.89	17.6					16.62	17.55				
125	45	17.97	19.6					18.49	19.79				
125	55	17.6	18.24					17.68	18.38				
125	65	16.37	16.33					16.65	16.65				
125	75	14.53	14.5					14.65	14.9				
125	85	13.24	12.96					13.63	13.29				

Appendix 3.4 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
		Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
Distance from emitter	Depth (cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
125	95	12.46	12.92					12.83	12.87				
125	105	12.45	12.67					12.31	12.35				
125	115	12.06	12.01										

Appendix 3.5 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 1.2 l h^{-1} emitter rate on a luvic fine sand

Time of measurement (h)		0		14.9		37.24		109.24		124.14	
		Control		20 mm		50mm		Redistribution		20mm (wet)	
Distance from emitter	Depth (cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	4.09	3.96	18.15	16.58	15.61	15.74	13.18	14.03	18.13	18.12
5	15	7.7	7.71	20.69	20.31	20.78	22	19.79	20.55	21.79	22.89
5	25	11.08	11.68	21.81	20.28	22.7	23.66	22.54	23.02	23.34	24.48
5	35	13.82	13.68	19.81	16.45	22.93	22.85	22.12	23.18	23.58	24.3
5	45	12.85	12.99	15.06	13.45	20.97	20.83	20.44	20.54	21.98	22.06
5	55	11.48	11.89	12.02	11.84	18.74	18.11	18.68	18.99	20.46	20.42
5	65	11.02	11.36	11.21		16.24	14.96	17.48	16.7	18.5	17.66
5	75	11.31	11.83	11.27		14.19	12.75	15.79	14.22	16.77	15.61
5	85	12.43	13.25			13.33	13.28	14.57	13.5	15.98	14.52
5	95	13.12	14.24			13.4	13.93	13.58	14.22	14.02	14.08
5	105							13.23	14.57	13.54	14.48
25	5	4.01	4.22	16.4	14.27	14.67	14.54	13.22	13.27	17.78	16.32
25	15	7.87	7.96	20.6	17.16	20.65	19.79	19.81	18.97	22.09	20.39
25	25	11.35	11.77	21.32	16.77	22.88	21.92	22.03	22.14	23.4	22.51
25	35	14.84	15.1	19.79	16.32	23.67	22.85	23.06	22.97	24.12	23.69
25	45	14.7	14.51	15.27	14.75	21.75	21.07	21.65	20.96	22.84	22.07
25	55	12.61	12.3	12.52	12.08	18.7	17.61	19.19	18.3	20.1	19.6
25	65	11.01	10.94			16.04	13.91	16.96	15.94	18.01	16.62

Appendix 3.5 (continue)

Time of measurement (h)		0		14.9		37.24		109.24		124.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
25	75	10.99	11.71			13.4	12.27	15.2	13.49	16.52	15.07
25	85	12.25	13.34			12.82	13.37	13.79	13.74	15.21	14.34
25	95	12.84	14.39			13.04	14.53	13.1	14.43	13.54	14.41
25	105							13.51	14.79	13.62	14.43
45	5	2.77	4.5	4.42	5.59	9.27	12.29	7.94	11.55	10.98	13.97
45	15	6.4	8.32	8.86	8.9	16.75	18.64	15.51	17.83	18.88	20.44
45	25	9.39	13.25	11.38	13.43	20.19	22.93	19.36	22.07	21.44	23.96
45	35	13.04	16.78	14.63	17.08	22.47	22.71	22.24	23.03	22.85	23.88
45	45	15.54	16.48	15.52	16.26	21.07	19.21	21.15	20.3	21.57	21.52
45	55	13.81	13.94	14.07		17.38	15.29	18.28	16.93	19.56	17.99
45	65	12.07	12.68	11.84		13.75	12.77	15.96	13.76	17.16	14.53
45	75	12.19	13			12.53	13.14	13.39	13.22	15.24	13.45
45	85	13.02	14.91			13.14		13.29	14.87	13.57	14.95
45	95	14.21	16.26			14.33		14.04	15.47	14.54	16.32
45	105							14.81	16.04	14.62	16.07
65	5	3.83	3.83	4.355	4.355	6.52	6.52	6.22	6.22	7.30	
65	15	8.075	8.075	8.68	8.68	12.93	12.93	12.73	12.73	14.23	
65	25	11.905	11.905	12.38	12.38	17.785	17.785	17.70	17.70	19.31	
65	35	14.945	14.945			19.21	19.21	19.24	19.24	20.16	
65	45	14.94	14.94			17.185	17.185	17.51	17.51	18.04	
65	55	13.06	13.06			14.405	14.405	15.31	15.31	15.66	
65	65	12.845	12.845			13.01	13.01	13.74	13.74	14.17	
65	75	12.725	12.725			12.83	12.83	13.10	13.10		
65	85	14.01	14.01					14.05	14.05		
65	95	14.67	14.67					14.71	14.71		
65	105							15.04	15.04		

Appendix 3.6 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 2 l h^{-1} emitter rate on a luvic fine sand

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	4.8	5.16	20.82	17.7	22.61	22.3	16.75	14.94	22.68	22.79	15.71	15.21
5	15	7.81	8.23	20.23	14.59	24.23	23.79	20.69	19.23	23.93	23.58	19.51	19.02
5	25	10.63	10.92	16.04	12.56	23.58	23.51	22.47	22.3	23.97	24.51	21.86	22.53
5	35	11.5	12.36	12.43	12.36	19.37	21.45	21.31	22.31	22.34	23.75	20.9	21.95
5	45	11.35	12.33	11.27	12.51	14.27	15.82	20.28	21.08	21.06	22.37	19.67	21.1
5	55	11.41	11.81	11.49	12.18	11.44	12.91	19.94	20.05	19.85	20.51	20.21	20.34
5	65	12.05	11.61			11.98	11.99	18.92	18.37	19.22	18.74	19.98	19.75
5	75	11.81	11.26			11.65	11.43	16.15	15.83	16.46	16.34	18.75	18.46
5	85	10.98	10.86					12.59	12.96	12.68	13.05	16.93	16.71
5	95	10.61	10.32					10.69	10.56	10.98	10.96	14.03	13.85
5	105	11.47	11.13					11.4	10.74			12.7	12.24
5	115	14.23	13.59									14.05	13.32
5	125	14.97	15.02									15.15	15.11
5	135	15.31	15.67									15.24	15.58
25	5	4.4	4.72	12.56	8.63	19.56	18.86	15.36	13.64	21.69	21.02	14.7	13.48
25	15	7.16	8.16	13	9.72	22.71	22.84	19.97	18.53	23.78	23.68	19.13	18.57
25	25	10.26	10.28	11.71	10.99	22.11	23.66	21.71	22.03	23.54	24.07	20.97	21.84
25	35	11.33	12.66	11.61	12.37	18.4	22.47	21.42	23.2	21.91	24.14	21.04	23.12
25	45	11.06	12.8	11.33	12.93	13.65	16.74	20.17	21.65	20.77	22.65	20.35	21.74
25	55	11.58	12.45			11.72	13.24	19.57	20.19	20.18	20.71	20.38	21.14
25	65	11.78	12			11.99	12.16	18.67	19.04	18.83	19.35	19.99	20.08
25	75	11.26	11.56			11.49	11.63	16.52	17.07	16.77	17.23	19.05	19.04
25	85	10.94	11.16					13.13	14.09	13.07	14.48	17.13	17.54
25	95	10.63	10.83					11.19	11.28	10.89	11.8	14.74	15.31
25	105	11.41	11.23					11.36	11.45			12.98	13.28
25	115	14.33	13.64									14.71	14.04
25	125	16.04	15.18									15.95	15.02

Appendix 3.6 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
	(cm)	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
45	5	4.1	4.62	4.54	4.89	7.3	7.28	13.09	10.83	18.65	14.61	13.16	11.2
45	15	6.89	8.12	7.07	8.03	12.32	11.39	17.61	16.37	21.56	19.6	17.11	17.08
45	25	9.96	10.72			15.61	14.65	21.12	20.75	23.38	23.11	21.33	21.37
45	35	12.5	13.4			14.18	14.78	22.16	22.8	22.55	24.75	22.22	23.05
45	45	12.53	14.54			12.6	14.8	20.37	22.32	20.74	22.98	20.79	23.19
45	55	12.36	13.86			12.49	13.78	19.04	20.8	18.92	20.91	19.68	21.62
45	65	11.96	12.92			12.12	13.12	17.25	18.61	17.43	18.5	18.82	20.16
45	75	11.44	12.34					14.44	15.6	14.8	15.86	17.6	18.95
45	85	11.06	11.65					11.98	12.9	11.89	12.91	15.45	17.47
45	95	10.86	11.55					10.99	11.75	11.16	11.93	13.1	14.67
45	105	11.89	12.09					11.7	12.16			12.01	12.79
45	115	14.33	14.93									14.21	14.63
65	5	4.47	5.38			4.28	5.45	8.09	6.45	8.67	6.86	9.4	7.92
65	15	7.09	8.3			7.34	8.34	12.28	10.79	12.62	11.44	13.92	13.43
65	25	9.78	10.66			9.84	11.05	16.21	15.63	16.84	16.38	17.89	17.64
65	35	12.5	13.63			12.72	13.6	19.12	18.51	19.74	19.05	21.08	20.67
65	45	14.45	14.3			14.43	15.12	19.44	19.04	19.53	19.09	21.01	20.58
65	55	13.32	13.75			13.46	13.99	16.62	16.78	17.04	17.19	18.85	19.15
65	65	12.37	13.51			12.47	13.37	13.69	15.05	13.69	15.21	16.81	18.37
65	75	11.91	13.02					12.26	13.79			15	17.08
65	85	11.65	12.89					11.51	12.89			12.74	15.58
65	95	11.81	12.34									12.04	13.77
65	105	12.31	12.74									12.17	12.72
85	5	4.35	5.42			4.24	5.61	4.47	5.37	4.69	5.32	4.93	5.45
85	15	7.04	8.46			6.94	8.61	7.37	8.62	7.46	8.61	8.38	9.11
85	25	9.22	11.02			9.19	11.45	10.31	11.6	10.36	11.92	12.61	13.02
85	35	11.62	14.8			11.97	14.42	12.79	14.82	12.63	15.05	16.03	15.82

Appendix 3.6 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
85	45	14.65	17.26			14.81	16.79	15.09	17.48			17.43	18.12
85	55	14.17	16.65			14.45	16.62	14.58	16.81			15.8	17.89
85	65	12.97	15.37			13.24	15.45	13.03	15.22			13.61	16.41
85	75	12.34	14.56					12.62	14.71			12.75	14.88
85	85	12.35	13.74					12.04	13.63			11.85	13.88
85	95	12.13	12.92					11.81	13.45			12.11	13.15

Appendix 3.7 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 8 l h^{-1} emitter rate on a luvic fine sand

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	3.29	3.75	20.68	22.79	20.66	22.47	12.98	14	20.39	22.38	12.61	13.93
5	15	6.8	7.31	19.51	21.26	23.06	23.63	18.84	19.34	22.48	23.46	19.24	19.05
5	25	9.92	10.45	14.25	15.18	23.21	23.77	22.02	22.55	23.65	24.14	22.29	22.91
5	35	13.02	12.95	13.69	13.53	21.45	23.13	23.45	23.86	24.39	25.49	24.36	24.81
5	45	14.05	13.4	14.12	13.27	16.04	16.95	21.53	22.19	22.03	23.18	22.47	23.11
5	55	13.66	12.98			13.67	13.37	19.49	20.34	19.16	20.47	20.58	21.5
5	65	12.95	12.11			12.92	11.96	17.23	18.6			19.49	20.1
5	75	12.37	11.53					14.65	15.76			18.05	18.54
5	85	11.97	11.1					12.27	12.81			16.56	16.79
5	95	12	11.35					12.15	11.55			14.89	15.23
5	105	13.81	13.6					13.74	13.62			14.59	15.19
5	115	16.71	16.67									17.02	16.79
25	5	3.37	3.69	14.78	10.79	19.91	20.26	12.29	12.46	19.64	20.34	12.91	13.19
25	15	6.66	7.32	13.87	10.56	23.37	23.02	18.35	18.08	22.58	23.15	18.62	18.73
25	25	9.84	10.51	11.49	11.3	23.03	23.41	21.62	21.17	23.97	24.15	21.42	22.28
25	35	13.18	13.13	13.44	13.48	21.37	20.1	23.17	22.65	25.13	24.44	24.34	23.58

Appendix 3.7 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
25	45	15.34	14.06	15.19	13.68	17.31	15.22	21.92	21.07	22.47	21.46	23	22.13
25	55	14.5	13.65			14.29	13.7	18.95	19.52	19.28	19.31	20.27	21
25	65	13.82	12.83					16.83	17.31			18.74	19.5
25	75	12.74	12.25					14.07	14.14			17.46	18.24
25	85	12.42	11.71					12.82	12.01			15.62	16.44
25	95	12.62	11.9					12.29	11.92			14.35	14.76
25	105	14.95	14.12									14.68	14.76
25	115	18.15	17.45									18.49	17.8
45	5	3.42	3.9	4.28	4.54	15.05	17.66	10.19	11.12	18.92	21.68	12.05	12.68
45	15	6.75	7.5	7.38	7.9	17.6	18.72	16.54	17.44	22.52	22.91	18.34	18.77
45	25	10.44	11.46	10.53	11.18	16.3	15.93	19.79	20.69	22.81	23.83	21.81	22.33
45	35	13.71	14.67	14.34	14.73	15.47	15.57	21.88	21.72	23.21	23.79	24.28	23.82
45	45	17.05	16.15			17.18	16.29	22.49	21.27	23.16	21.19	24.1	22.87
45	55	16.52	15.27			16.69	15.39	20.05	19.04	19.62	18.95	21.51	21.16
45	65	14.97	14.23			14.82	14.17	16.79	15.93			19.3	19.39
45	75	13.83	13.13					14.61	13.21			17.41	16.92
45	85	12.98	12.58					13.22	12.7			14.68	14.92
45	95	13.1	12.6					12.92	12.59			13.41	13.19
45	105	15.23	15.23									14.98	15.32
65	5	3.63	3.46	3.8	3.53	4.87	4.76	5.92	5.85	11.55	18.43	10.45	11.71
65	15	7.56	7.34	7.42	7.26	8	8.02	10.29	10.49	13.04	19.42	16.38	17.37
65	25	11.03	10.91	10.75	10.94	11	11.2	13.18	14	14.19	17.18	18.54	20.83
65	35	14.2	13.82	14.15	13.97			15.8	16.32	15.56	17.24	20.25	22.72
65	45	17.17	16.43					18.47	17.61	18.55	17.7	22.15	22.23
65	55	17.59	16.2					18.17	16.79			20.71	20.17
65	65	16.46	14.92					16.36	15.04			17.57	17.76
65	75	14.57	13.54					14.84	13.84			15.59	15.62
65	85	13.53	12.73					13.36	12.85			13.99	13.5
65	95	12.97	12.85									13.34	13.23

Appendix 3.7 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
65	105	14.87	15.29									14.67	15
85	5	4.25	3.56			4.44	3.53	4.5	3.72	4.63	5.04	6.09	6.24
85	15	8.07	7.34			8.29	7.39	8.33	7.57	8	8.06	10.45	10.54
85	25	11.67	11.23					11.8	11.06	12.16	11.43	13.03	14.39
85	35	14.99	13.96					14.87	14.07	15.06	13.73	15.53	16.83
85	45	17.92	17.15					17.91	16.96			18.36	18.27
85	55	17.6	16.77					17.83	17.25			18	17.25
85	65	16.11	15.26					16.32	15.11				
105	5	3.44	3.3					3.72	3.28			3.87	3.56
105	15	6.69	6.47					6.72	6.83			7.11	6.94
105	25	10.61	10.28					10.63	10.55			10.64	10.8
105	35	13.94	13.36					13.77	13.58			14.07	13.49
105	45	17.63	16.42					17.24	16.51				

Appendix 3.8 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 1.2 l h^{-1} emitter rate on a sandy clay loam

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	3.39	5.92	13.15	15.94	14.72	17.23	11.48	14.36	14.24	17.37	12.25	15.08
5	15	13.03	15.67	24.7	24.82	26.16	25.84	23.41	24.2	25.59	25.89	24.64	24.75
5	25	20.24	20.79	25.75	24.92	26.78	26.35	25.79	25.5	26.94	26.97	26.69	26.11
5	35	22.94	22.44	26.19	23.91	28.14	27.88	27.79	27.26	28.58	28.17	27.96	27.91
5	45	23.83	24.14	24.19	24.34	29.37	28.58	29.19	28.52	29.38	29.01	29	29.06
5	55	23.95	24.04	23.34	23.7	28.24	28.23	28.75	28.92	29.08	28.93	29.02	29.1
5	65	23.07	22.98	22.98	23.27	26.73	26.12	28.02	27.41	27.7	28.21	28.14	28.47
5	75	22.91	23.55			24.77	24.64	25.93	25.8	27.21	28.1	28.11	27.71
5	85	24.43	24.36			24.34	23.97	24.89	24.56	26.99	26.22	28.05	27.66
5	95	24.87	23.62					24.9	23.91	26.26	24.02	27.28	25.32
5	105	24.66	23.51					24.56	23.66	24.85	23.71	25.46	24.25
5	115	23.47	23.98									22.95	23.8
25	5	5.88	7.9	15.22	17.79	16.56	19.32	14.59	17.11	16.97	19.43	15.12	17.94
25	15	15.56	17.61	25.15	25.08	26.71	26.77	24.97	25.39	26.54	26.8	25.17	25.76
25	25	20.71	21.12	26.26	24.35	27.88	27.37	26.59	26.42	28.12	27.77	27.28	27.09
25	35	23.22	22.85	25.05	23.09	28.9	28.77	28.17	28.47	29.15	29.2	28.86	28.88
25	45	24.34	23.73	24.05	24.03	29.86	28.2	29.46	29.14	30.33	30.22	29.99	30.18
25	55	24.24	24.33	24.35	24.69	29.16	26.57	29.53	28.1	29.89	29.56	29.93	30.12
25	65	24.11	24.08	23.45	24.62	26.7	25.36	28.23	26.75	29.32	28.3	29.32	29.45
25	75	24.84	25.48			25.86	25.73	26.39	26.73	28.14	27.34	28.88	28.68
25	85	24.88	25.7			25.13	26	25.99	26.03	27.6	26.44	29.01	27.41
25	95	24.61	24.68					24.85	25.2	26.28	25.29	26.65	25.48
25	105	24.28	24.42					24.28	24.16	24.64	23.63	24.87	24.18
25	115	23.62	23.12									23.5	23.1
45	5	7.26	6.01	11.83	8.39	18.33	14.95	16.52	13.7	18.33	15.93	16.94	14.78
45	15	16.39	15.42	19.06	17.22	24.91	25.17	23.92	24.3	24.87	25.3	24.27	24.68
45	25	20.76	21.56	21.93	21.64	25.98	27.48	26.17	27.15	26.87	27.94	26.66	27.34
45	35	23.37	24.02	23.67	24.07	25.89	26.84	27.42	28.16	28.01	29.43	27.87	29
45	45	24.29	24.52	23.89	25.12	25.71	25.42	27.65	27.16	28.22	28.53	29.08	29.37

Appendix 3.8 (continue)

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
45	55	23.57	24.49	23.91	24.57	24.55	24.91	25.44	25.66	26.14	26.06	27.56	28.11
45	65	23.19	24.76	23.2	24.85	23.36	24.63	23.65	24.48	24.56	25.07	25.96	25.71
45	75	22.92	24.19			23.18	24.3	23.04	24.36	23.67	24.51	23.95	24.68
45	85	22.17	23.67			22.69	23.63	22.76	23.37	23.28	23.67	23.74	24.16
45	95	21.68	23.64					22.68	23.54	23.48	23.56	23.03	23.72
45	105	22.48	23.85					23.05	23.78			23.19	23.83
45	115	21.87	23.34									22.24	23.43
65	5	7.82	6.67	7.68	6.52	15.32	12.14	15.92	13.25	17.02	14.7	16.63	14.28
65	15	16.67	15.51	16.6	15.66	24.08	21.95	24.37	23.06	26	24.02	25.26	23.61
65	25	21.82	20.75	21.77	21.14	24.19	23.25	25.49	25.32	26.37	25.7	26.38	26.25
65	35	23.42	22.5	23.33	21.99	23.77	22.41	25.07	24.82	25.32	25.37	27.26	26.41
65	45	24.45	22.58	23.92	22.94	24.4	22.69	24.88	23.57	24.9	23.49	27.09	26.31
65	55	24.19	23.03	24.13	22.92	24.14	23.08	24.31	23.24	24.3	23.36	24.96	23.98
65	65	23.26	22.91	23.53	22.51	23.89	23.15	23.4	22.9	23.82	22.62	23.71	23
65	75	22.77	22.4			22.7	21.84	22.69	22.11	22.67	22.21	22.91	22.22
65	85	22.28	21.12			21.89	20.88	22.04	20.93	22.06	20.98	22.17	21.27
65	95	21.37	20.89					21.04	21.43			21.27	21.1
65	105	21.76	21.56					21.96	22.13			21.96	22.2
65	115	21.9	22.02									22.18	22.12
85	5	6.94	8.79			7.09	8.92	9.76	10.76	11.11	11.48	13.36	13.38
85	15	16.76	18.29			16.92	18.92	20.17	20.87	21.21	21.93	22.45	22.96
85	25	22.89	23.65			22.93	24.13	24.05	24.69	24.53	24.81	25.27	25.99
85	35	24.62	25.05			24.29	24.92	24.5	25.19	24.71	25.36	25.5	25.17
85	45	24.17	24.46			24.02	24.68	24.6	24.21	24.6	24.42	24.85	24.21
85	55	23.73	24.25			23.95	23.85	23.87	23.97	23.95	24.19	23.95	23.85
85	65	23.47	23.4			23.57	23.33	23.5	23.22	23.7	23.32	23.59	23.46
85	75	24.12	23.49			23.53	23.22	23.91	23.43	24.41	23.33	23.96	23.34
85	85	24.25	23.8					23.53	23.71			23.85	23.82
85	95	24.11	23.38					23.59	23.4			23.57	23.61

Appendix 3.8 (continue)

Time of measurement (h)		0		14.9		37.24		109.24		124.14		196.14	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
85	105	23.42	23.39					23.34	23.84			23.71	23.38
85	115	23.2	22.67									22.67	22.51
105	5	8.24	11.39					8.17	11.66			9.07	10.96
105	15	16.79	20.44					17	20.32			18.38	20.53
105	25	21.72	23.47					21.75	23.34			22.4	23.75
105	35	23.67	24.41					23.85	24.73			23.69	24.75
105	45	23.84	24.56					24.06	24.98			24.36	24.76
105	55	23.73	24.35					23.92	24.16			23.89	24.16
105	65	23.73	23.43					23.86	23.97			23.77	24.23
105	75	23.07	23.23					23.51	23.86			23.56	24.03
105	85	23.54	23.59					23.62	23.76			23.62	23.23
105	95	23.9	23.55					24.36	23.69			24.05	23.79
105	105	24.01	23.17									23.58	23.12
105	115	22.7	22.9									23.02	23.07

Appendix 3.9 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 2 l h^{-1} emitter rate on a sandy clay loam

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	11.09	6.48	23.57	19.66	23.99	19.72	20.79	15.95	22.98	19.12	20.01	15.35
5	15	18.23	16.02	22.98	23.76	24.48	24.35	23.51	23.08	24.02	24.13	23.7	23.24
5	25	20.9	20.08	21.72	22.63	25.41	25.36	24.94	24.73	25.83	25.23	25.24	25.18
5	35	22.23	21.78	22.26	22.08	25.12	26.56	26.41	25.86	26.68	27	26.62	26.36
5	45	22.35	22.09	22.42	22.28	22.94	25.39	24.96	26.17	24.45	26.64	26.05	27.04
5	55	22.26	22.11	22.31	21.44	22.13	23.2	22.57	24.41	22.51	24.25	23.05	25.26
5	65	20.93	21.62	20.97	21.39	21.37	21.29	21.32	21.72	20.91	21.79	21.21	22.05
5	75	19.72	20.03			19.96	20.01	20.13	20.1			20.14	20.15
5	85	19.99	19.92			19.8	20.06	20.1	20.2			19.74	19.98
5	95	22.67	22.07					22.19	22.15				
5	105	24.58	23.72					24.8	23.56				
25	5	11.28	12.31	21.95	21.89	21.91	23.08	19.69	20.51	22.24	22.3	20.49	21.26
25	15	18.36	18.84	21.7	22.19	23.99	24.83	23.61	23.7	24.12	24.29	23.75	24.07
25	25	20.7	21.53	21.58	21.78	24.53	25.56	24.7	25.02	25.44	26.08	25.08	25.72
25	35	21.73	22.48	22.23	21.99	23.68	25.79	25.55	26.22	26	26.81	25.93	27
25	45	21.88	22.38	21.67	22.42	22.09	23.57	24.16	25.69	23.65	25.84	25.41	26.68
25	55	21.67	21.72	22.13	21.66	21.69	22.08	21.81	22.91	22.26	22.89	22.46	23.65
25	65	21.15	21.03	21.07	20.69	21.37	20.91	21.07	20.88	21.36	20.98	21.34	21.69
25	75	20.47	20.2			20.56	20.17	20.62	20.49			20.63	20.31
25	85	21.05	20.88			21.09	20.72	20.79	20.87			21.39	20.92
25	95	23.92	22.4					23.65	22.13				
25	105	24.92	22.17					24.79	22.22				
45	5	10.83	11.17	17.09	15.79	22.66	23.91	19.87	19.81	22.06	23.06	20.17	20.02
45	15	17.3	17.48	18.29	18.68	25.52	25.36	23.78	24.22	25.23	25.23	23.76	23.68
45	25	20.77	21	20.62	21.28	24.78	25.73	24.88	25.04	25.59	25.99	25.12	25.02
45	35	22.26	21.93	22	22.13	23.22	24.29	25.54	25.58	25.36	25.73	25.86	26.57
45	45	22.38	21.76	22.26	21.53	22.38	22.54	23.43	23.77	23.51	24.31	24.58	25.09

Appendix 3.9 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
45	55	21.99	21.67	22.2	21.55	22.45	21.56	22.35	22.19	22.41	22.07	22.65	22.98
45	65	21.37	20.93	21	20.63	21.38	20.92	21.45	20.57	21.07	20.76	21	20.93
45	75	20.86	20.61			20.7	20.68	20.49	20.47			20.91	20.44
45	85	21.15	22.23			21.31	22.15	21.33	21.99				
45	95	22.81	24.07					22.58	23.77				
45	105	23.01	23.93					23.02	24.05				
65	5	8.93	9.27	9.02	9.29	19.56	20.47	17.07	17.36	19.55	19.78	17.4	17.42
65	15	15.88	16.28	16.15	16.92	24.29	25.08	22.23	22.62	24	24.67	22.86	23.22
65	25	20.53	21.36	20.54	21.64	24.24	24.92	24.78	25.34	25.64	26.33	24.97	25.36
65	35	21.82	22.78	20.83	22.46	21.88	23.12	24.4	25.74	24.48	26.37	26.12	26.79
65	45	22.08	22.57	21.38	22.68	21.79	22.55	22.66	23.32	22.47	23.11	23.65	24.97
65	55	22.01	21.81	21.83	21.68	21.7	21.81	22.12	21.87	21.6	21.88	22.16	22.48
65	65	21.43	21.6			21.14	21.55	21.14	21.6	21.26	21.58	21.03	21.37
65	75	21.1	21.94			20.61	21.62	20.85	21.42			21	21.86
65	85	23.84	23.51					23.47	23.25				
65	95	24.92	24.24					25.11	24.45				
65	105	24.27	23.9					24.72	23.77				
85	5	7.35	9.13			8.19	10.23	10.66	12.85	10.6	12.93	12.05	14.52
85	15	15.81	16.99			16.81	17.75	20.04	20.8	19.97	20.78	20.69	21.73
85	25	20.6	21.07			20.86	20.77	22.57	22.89	22.86	23.07	23.92	24.41
85	35	21.55	21.59			21.41	21.87	22.59	22.46	22.83	22.5	23.77	24.07
85	45	21.97	21.81			21.47	22.14	22.12	21.92	22.05	21.78	22.74	22.25
85	55	21.75	21.82			21.45	21.75	21.71	21.87	21.83	21.96	21.92	22.26
85	65	21.23	21.47			21.18	20.87	21.6	21.26	21.1	21.36	21.5	21.5
85	75	20.99	21.32			20.78	20.95	21.26	21.16			21.31	21.54
85	85	22.18	21.69					22.31	21.59				
85	95	22.23	21.36					22.35	21.71				
85	105	22.86	21.59					22.71	21.61				

Appendix 3.9 (continue)

Time of measurement (h)		0		7.45		18.62		90.62		98.07		170.07	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
105	5	7.03	9.79			7.34	9.81	7.49	10.22			8.39	10.33
105	15	15.43	17.18			15.58	17.3	15.65	17.03			16.25	18.07
105	25	19.87	21.01			20.51	20.78	20.45	20.67			20.39	21.04
105	35	21.36	22.06			21.4	21.86	21.76	22.04			21.83	22.46
105	45	21.63	21.64			21.81	22.12	21.86	22.56			22.12	22.13
105	55	21.8	22.42			21.51	22.08	21.81	22.28			21.58	22.2
105	65	20.89	21.7			21.42	21.52	21.13	21.74			21.08	21.5
105	75	21.09	21.95			21.42	21.99	21.29	21.78			21.74	22.09
105	85	21.97	23.79					22.3	23.31				
105	95	22.49	23.72					22.34	23.55				
		21.84	23.48					22.17	23.4				

Appendix 3.10 Neutron probe readings (mm water per 100 mm soil depth) for the strip perpendicular (below) and between emitters after a given amount of water was applied or allowed for redistribution for the 8 l h^{-1} emitter rate on a sandy clay loam

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	5	15.24	14.61	23.85	24.41	24.59	25.37	22.84	23.31	24.22	25.13	22.72	23.28
5	15	19.79	20.11	22.14	22.01	24.36	24.65	24.58	24.46	24.85	25.38	24.48	24.53
5	25	21.92	22.41	22.44	23.15	23.75	24.14	24.86	26.02	25.48	25.83	26.16	26.35
5	35	22.89	23.61	22.63	23.58	22.79	24	24.16	25.05	24.52	24.9	26.09	26.41
5	45	22.47	23.03	22.38	23.11	22.4	23.66	22.66	24.02	22.76	24.27	23.41	24.94
5	55	22.33	23.52	22.52	23.6	22.47	23.32	22.51	23.47	22.39	23.42	22.42	23.84
5	65	22.06	22.8	22.21	22.47	22.12	22.99	22.35	22.66			22.31	22.83
5	75	21.79	23.09			21.3	22.55	21.83	22.78			21.88	22.69
5	85	23.17.	23.88					22.89	23.73				

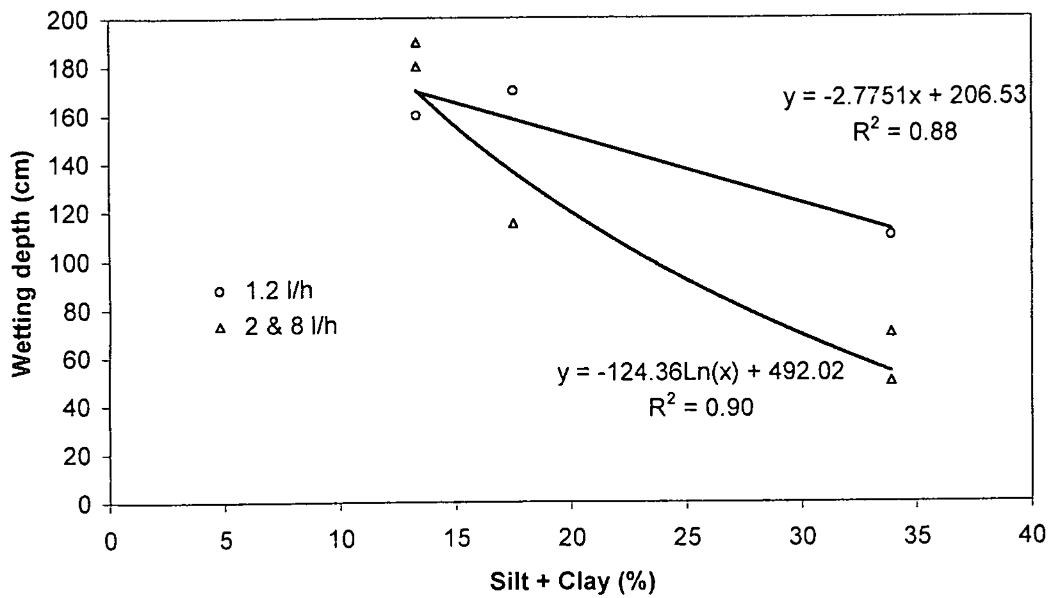
Appendix 3.10 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
5	95	24.37	24.66					24.36	25.04				
5	105	24.85	25.33					24.48	25.19				
25	5	12.75	10.61	24.26	22.66	24.99	24.42	22.22	20.45	24.78	22.83	22.52	20.11
25	15	18.65	17.44	22	20.79	25.64	24.6	24.74	23.6	25.89	25.02	24.81	24.06
25	25	22.41	21.51	22.83	21.81	24.32	24.65	26.02	25.42	26.45	25.62	26.68	25.42
25	35	22.93	22.61	22.94	22.59	22.86	23.13	25.15	25.03	24.89	24.85	26.68	26.24
25	45	23.21	22.55	23.32	22.77	23.11	22.89	23.28	23.53	23.77	23.66	24.09	24.6
25	55	23.55	22.19	23.51	22.52	23.3	22.68	23.7	22.61	23.53	22.65	23.61	22.82
25	65	22.83	22.22	22.69	22.46	22.69	21.99	22.84	22.02			22.88	22.05
25	75	22.5	22.77			22.88	22.75	22.27	22.81			22.8	23.08
25	85	24.67	23.71					24.83	23.85				
25	95	26.08	23.92					26.1	23.85				
25	105	25.6	23.82					25.37	24.19				
45	5	12.72	11.18	20.86	14.68	24.28	22.81	21.39	19.89	23.43	21.44	21.62	20.11
45	15	18.46	17.73	19.53	17.75	24.59	23.66	24.05	23.1	25.27	23.98	24.61	23.57
45	25	20.77	21.24	21.33	21.39	23.54	23.29	24.69	24.89	25.47	25.32	25.5	25.57
45	35	22.3	22.61	21.98	22.67	22.59	22.91	23.96	23.92	23.73	24.17	25.08	25.01
45	45	22.91	22.36	23.03	22.32	22.85	22.07	23.37	22.82	23.29	22.62	23.83	23.43
45	55	23.52	22.65	23.38	22	23.73	21.87	24	22.16	23.21	22.14	23.6	22.54
45	65	23.51	21.47	23.29	21.65	23.41	21.69	23.71	21.45			23.58	21.7
45	75	23.22	21.34			23.42	21.53	23.15	21.36			23.36	21.14
45	85	24.11	21.37					24.04	21.41				
45	95	24.99	21.44					24.93	21.16				
45	105	24.97	22.83					25.16	22.35				
65	5	12.12	11.77	12.37	11.64	18.13	17.1	18.74	17.88	19.76	19.21	19.49	18.97
65	15	18.21	17.88	18.4	17.42	20.16	18.65	23.08	21.87	23.19	21.92	23.7	23
65	25	22.1	20.43	21.92	21.13	21.97	21.54	24.02	23.33	24.25	23.26	25.42	24.63
65	35	22.85	22	23.15	21.7	22.79	21.49	23.3	22.43	23.64	22.03	24.43	23.01

Appendix 3.10 (continue)

Time of measurement (h)		0		1.94		4.86		76.86		78.8		150.8	
Distance from emitter	Depth (cm)	Control		20 mm		50mm		Redistribution		20mm (wet)		Redistribution (wet)	
		Below	Between	Below	Between	Below	Between	Below	Between	Below	Between	Below	Between
65	45	23.49	22.46	23.97	22.6	23.58	22.36	23.58	22.61	23.63	22.58	23.7	22.72
65	55	23.95	23.38	23.92	22.65	23.91	23.17	23.71	22.86	23.57	22.86	23.87	23.03
65	65	22.86	22.42	23.16	22.38	23.15	22.46	23.57	22.29			23.38	21.89
65	75	23.69	22.61			23.48	22.36	22.92	22.5			23.32	22.46
65	85	24.56	22.03					24.19	22.47				
65	95	24.78	21.55					25.04	21.64				
65	105	25.64	21.22					25.18	21.71				
85	5	11.56	10.17			11.71	10.75	14.32	12.32	14.13	12.65	15.79	13.55
85	15	18.06	16.52			18.24	16.45	18.96	16.98	19.18	16.64	20.46	17.94
85	25	22.1	20.43			22	20.51	22.06	20.71	22.07	20.58	23.2	21.03
85	35	23.24	21.67			23.15	22.23	23.19	21.85	23.13	21.63	23.25	21.95
85	45	23.67	22.85			23.78	22.81	23.86	22.39	23.98	22.18	23.67	22.19
85	55	23.77	22.3			24.04	22.47	23.57	21.92	23.52	22.26	23.5	22.35
85	65	22.91	21.44			22.96	21.58	22.81	21.57			23.17	21.51
85	75	22.96	21.14			23.01	21.15	23.29	21.05				
85	85	23.5	20.44					22.89	20.58				
85	95	23.34	20.75					23.59	20.45				
85	105	23.13	20.81					23.33	20.71				
105	5	10.36	7.02					10.17	6.79			10.56	6.53
105	15	17.47	14.17					17.89	13.92			17.83	14.19
105	25	22.66	20.85					22.38	20.45			22.59	20.61
105	35	23.26	22.55					23.59	22.56			23.73	22.69
105	45	23.45	22.65					23.51	22.78			23.47	22.86
105	55	23.16	22.72					23.38	22.96			23.65	22.9
105	65	22.74	22.48					22.94	22.33			22.73	22.28
105	75	23.11	22.61					22.87	22.55				
105	85	22.42	22.81					22.76	23.03				
105	95	22	23.72					22.11	23.02				
105	105	22.12	23.39					22.01	23.85				

Appendix 4.1 The relationship between wetting depth and silt plus clay (%) for applying 20 mm irrigation on a wet soil following redistribution.



Appendix 5.1 Nitrate concentration (mg kg^{-1}) for nitrates applied at the beginning and end of the irrigation event and with additional 20 mm irrigation for strips perpendicular (below) and between emitters

Time of measurement (h)		79.45		158.9		79.45		158.9		0
Distance from emitter	Depth (cm)	Nitrate injected at beginning of first 20 mm irrigation followed by 3 days redistribution		After second 20mm irrigation plus 3 days redistribution		Nitrate injected at end of first 20 mm irrigation followed by 3 days redistribution		After second 20mm irrigation plus 3 days redistribution		Control
		Below	Between	Below	Between	Below	Between	Below	Between	
5	5	5.92	111.16	2.48	33.41	421.75	64.15	2.48	99.35	6.84
5	15	22.34	160.57	5.53	50.80	260.81	16.40	71.72	70.20	8.12
5	25	39.51	143.65	15.83	47.02	99.49	15.14	89.59	46.57	8.78
5	35	54.48	100.21	23.16	36.65	13.50	17.38	103.55	21.73	9.79
5	45	37.02	27.91	24.88	17.01	27.83	12.66	45.16	15.48	8.15
5	55	15.18	8.96	21.12	11.10	17.58	7.25	13.21	14.39	5.64
5	65	3.23	5.62	16.58	11.02			6.79	10.76	5.67
5	75			16.92	15.28			8.12		6.47
5	85			7.89	4.92					9.85
25	5	70.31	124.19	64.97	123.87	63.43	59.23	12.00	68.81	
25	15	80.90	58.51	25.99	78.18	16.06	20.43	12.09	37.24	
25	25	41.90	71.15	38.31	31.81	21.73	16.32	20.18	29.99	
25	35	13.43	29.11	40.71	19.97	18.59	12.38	37.16	20.06	
25	45	6.57	6.17	25.57	12.20	9.58	10.25	11.20	13.35	
25	55	8.66	7.12	17.40	10.65			8.40	10.33	
25	65			10.50	9.18			6.48		
25	75			4.92	7.51					
25	85			3.17	6.07					
45	5	80.46	109.52	144.33	159.94	79.12	56.96	65.07	65.50	
45	15	58.51	45.08	76.09	55.42	34.57	26.79	41.24	25.70	
45	25	34.93	26.57	45.47	28.41	15.66	12.40	21.47	17.21	
45	35	17.17	14.48	19.50	16.54	19.11	11.74	12.40	13.47	
45	45	9.95	8.21	8.89	9.42	8.55	9.64	10.74	13.44	
45	55	5.27	6.52	5.71	6.62			7.68	10.50	
45	65			3.71	3.05					
45	75			2.85	3.89					
65	5	47.82	37.67	87.63	85.36	23.34	88.85	35.00	27.43	
65	15	18.81	15.92	26.84	24.30	14.48	25.59	19.63	21.33	

Appendix 5.1 (continue)

Time of measurement (h)		79.45		158.9		79.45		158.9	
Distance from emitter	Depth (cm)	Nitrate injected at beginning of first 20 mm irrigation followed by 3 days redistribution		After second 20mm irrigation plus 3 days redistribution		Nitrate injected at end of first 20 mm irrigation followed by 3 days redistribution		After second 20mm irrigation plus 3 days redistribution	
		Below	Between	Below	Between	Below	Between	Below	Between
65	25	24.08	21.94	28.72	25.85	11.94	11.68	14.39	17.96
65	35	22.39	14.23	20.51	28.85	9.58	9.56	9.70	15.25
65	45	12.44	9.55	11.96	11.49	9.81	7.97	6.45	10.91
65	55			3.40	6.27				
65	65			4.35	7.08				
85	5			52.16	42.81				
85	15			15.55	17.92				
85	25			27.12	13.18				
85	35			24.76	20.99				
85	45			14.32	13.52				
85	55			11.50	10.41				