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Root zone solute dynamics under drip irrigation: A review

Khumoetsile Mmolawa and Dani Or*
Department of Biological and Irrigation Engineering and Dept. of Plants, Soils and Biometeorology, Utah State University, Logan, UT 84322-4820, USA

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Abstract

Infiltration and subsequent distribution of water and solutes under cropped conditions is strongly dependent on the irrigation method, soil type, crop root distribution, and uptake patterns and rates of water and solutes. This review discusses aspects of soil water and solute dynamics as affected by the irrigation and fertigation methods, in the presence of active plant uptake of water and solutes. Fertigation with poor quality water can lead to accumulation of salts in the root zone to toxic levels, potentially causing deterioration of soil hydraulic and physical properties. The high frequency of application under drip irrigation enables maintenance of salts at tolerable levels within the rooting zone. Plant roots play a major role in soil water and solute dynamics by modifying the water and solute uptake patterns in the rooting zone. Modeling of root uptake of water and solutes is commonly based on incorporating spatial root distribution and root length or density. Other models attempt to construct root architecture. Corn uptake rate and pattern of nitrate nitrogen was determined from field studies of nitrate dynamics under drip irrigation using TDR monitoring. The determined nitrate nitrogen uptake rates are within literature values for corn.

Introduction

Because of its highly localized application and the flexibility in scheduling water and chemical applications, drip irrigation has gained widespread popularity as an efficient and economically viable method for fertigation. The method ensures that applied soluble plant nutrients become available to a substantial fraction of the plant root system; this is particularly important in sandy soils (Bar-Yosef, 1977; Bucks and Nakayama, 1980; Clothier, 1984). When using low quality water, drip irrigation has several advantages over other irrigation methods because it does not wet the foliage, and because of its high application frequency, concentrations of salts in the rooting zone remain manageable (Mantell et al., 1985). Thus, if operated and maintained properly, drip irrigation has the potential to improve nutrient management and increase farm profits. Whereas, if management is not properly practiced, fertigation with drippers can compound any existing salinity problems, and in some cases salts can even be leached beyond the rooting zone and pollute the underlying groundwater resources.

An increasing problem in todays modern irrigated agriculture is the declining availability of good quality irrigation water. This situation is mainly due to increased competition for water in large and ever growing urban and industrial areas around the world. According to Mantell et al. (1985), the result of this growing competition is the tendency to use waters which in the past were considered unsuitable for crops or even deleterious to soil properties, such as brackish water, recycled water, sewage water and industrial waste water.

Depending on the chemical composition of the brackish water or recycled wastewater used for fertigation with drippers, it may increase the amounts of total dissolved solutes leading to salinization of the soil. Salinity may induce unfavorable osmotic stresses, and at high levels become toxic for plants. The other problem that can arise from fertigation with saline water is the build up of soluble sodium in the soil that could adversely affect soil permeability. Toxicity of some ions to certain plants can also be a problem that arises from use of low quality water for irrigation.

* FAX No: (435) 797 2117. E-mail: dani@tal.agsci.usu.edu

Frenkel (1984) states that the influence of irrigation water on soil solution composition and concentration can be divided into the transient stage and equilibrium stage. The transient stage is when the soil water concentration is changing and reactions are occurring faster than at the equilibrium stage. Oster (1994) reported that use of poor quality water requires some changes from standard irrigation practices, such as selection of appropriately salt tolerant crops, improvements in water management and, in some cases, the adoption of advanced irrigation technology.

During infiltration, the soil water content changes both spatially and temporally. Fluctuations in soil water content affect the soil solution concentrations and composition, as well as influence subsequent solute distribution in the soil profile. Some solutes react with the soil matrix as they travel through the soil, resulting in dissolution and precipitation in or out of soil water solution. Variations in mobility and reactions by solutes result in different solute distribution. For example, nitrates are transported mainly by convection with streams of water, while the less mobile phosphates are transported by diffusion, and hence their subsequent distribution is bound to be different.

Salts largely fall into two categories, those that are easily taken up by plant roots and those that are excluded by plant roots. Both types of salts can either be highly mobile or relatively immobile in the soil. Their mobility affects the way they become available at the root zone of plants. As an example, if a solute is not mobile and not easily taken up by roots, then there will be a high concentration build-up of the solute in the root zone with subsequent applications of the solute.

Aspects of plant uptake of solutes within the active rooting zone introduce additional complexity to the modeling of solute dynamics. The analysis and measurement of solute movement and distribution becomes complicated due to uncertainty regarding root distribution and functionality within the root zone. Plant roots, because of their selective uptake of solutes, affect the concentration, movement and distribution of solutes within the root zone. Root uptake patterns of water and solutes are highly dynamic since the root distribution in the soil profile, water content and availability, and aeration status of the soil are in a constant state of change. Under ideal conditions, any attempt to measure root water uptake should consider not only these highly dynamic parameters in detail, but should also consider how they interact as well.

Water uptake by plant roots under saline conditions induces additional osmotic potentials and can raise toxicity levels. This can lead to roots being exposed to very different soil osmotic and matric water potentials from the bulk of the soil during the water depletion period. Hence, in order to improve the understanding of the processes of water supply to crops growing in saline conditions, the effects of decreasing osmotic and matric water potential in the soil surrounding the roots needs to be quantified (Schleiff, 1986).

Improved understanding of solute dynamics in the crop root zone should help to improve fertigation schedules for better drip irrigation management. It could reduce leaching of salts and, therefore, optimize nutrient uptake by plants, and provide the capability to control the application of saline water at the most salinity sensitive stage of the plants. It can also provide the opportunity for potential reuse of considerable amounts of water that is of low quality from other uses or users.

The irrigation and fertigation methods used to introduce salts and nutrients into the soil, as well as the salinity level of both the irrigation water and the resident soil water solution, affect root zone solute dynamics. Plant roots through their water and solute uptake play the dominant role in the root zone solute dynamics. The primary objective of this review is to elucidate root zone solute dynamics under drip irrigation. To achieve this objective, the review discusses and unifies several principles that are related to solute dynamics, such as soil physical and chemical processes, plant root uptake of water and solutes, as well as aspects of drip irrigation and fertigation. Because of the rapid changes and accentuated effects of root-zone dynamics, we focus the discussion and the motivating examples on annual crops with less reference to woody perennials.

The major topics covered in this review include a discussion of theoretical aspects of water flow from point and line sources in the 'Theoretical considerations' section. The modeling of solute transport by the convection dispersion equation (CDE) is followed by the numerical and analytical methods for solving the CDE. The 'Drip fertigation' section deals with aspects of drip irrigation and fertigation; it mainly discusses scheduling of fertigations and irrigation with water of low quality. The 'Characteristics of nutrient movement and distribution under drip irrigation' section describes general aspects of salts and nutrient movement under drip irrigation. The 'Root distribution' section deals with root distribution and parametric models, as well as root distribution and root water uptake patterns. The 'Modeling plant uptake of water and solutes' section covers modeling of water and solute uptake as well as root uptake of nutrients. The 'Monitoring nitrate dynamics- experimental evidence' section deals with macroscopic approximation to plant solute uptake by the volume balance model.

Theoretical considerations

Water flow and distribution from point and line sources

Drip irrigation systems are usually operated intermittently and consist of point or line sources, which are sometimes arrayed and interacting. For effective design and use of drip systems, there is a need to predict water movement from interacting sources (Merrill et al., 1978). Richards' equation, which combines Darcy's law with conservation of mass, is usually used to describe the three-dimensional infiltration and subsequent redistribution of water in the soil as (Clothier and Green, 1997; Coelho and Or, 1996; Molz, 1981):

$$\frac{\partial \theta}{\partial t} = \nabla.(K \nabla H) - Q \tag{1}$$

where θ is the volumetric water content (m^3 m^{-3}), H is the total (sum of matric head (h) and gravitational (z)) hydraulic head (m), K is the unsaturated hydraulic conductivity function (m s^{-1}), Q is a volumetric sink or source for water per given soil volume per time (m^3 m^{-3} s^{-1}), and ∇ is the spatial gradient operator.

Analytical solutions for Equation (1) are usually obtained by a linearization procedure (Philip, 1971) that employs the exponential form for the unsaturated hydraulic conductivity by Gardner (1958) as:

$$K(h) = K_s e^{ah} \tag{2}$$

K_s is the saturated hydraulic conductivity (m s^{-1}), and α is a parameter for the rate of reduction in hydraulic conductivity with h (m^{-1}). Additionally, the matrix flux potential transformation (ϕ):

$$\phi = \int_{-\infty}^{h} K(h)\mathrm{d}h = \frac{K(h)}{\alpha} \tag{3}$$

is introduced and used as the state variable for the quasi-linear solution.

The steady state solution for the distribution of ϕ about a buried point source in an infinite medium is usually obtained by using the following boundary condition:

$$\lim_{(r^2+z^2)^{0.8} \to \infty} \phi = 0 \tag{4}$$

where r is the radial distance from the source, z is the vertical coordinate, positive downward. With a known source strength q (m^3 s^{-1}) at r = 0 and z = 0, the solution for ϕ for a buried point source is (Or, 1995; Philip, 1968):

$$\phi_B(r,z) = \frac{q}{4\pi(r^2+z^2)^{0.5}} \exp\left[\frac{\alpha}{2}(z + (r^2+z^2)^{0.5})\right] \tag{5}$$

Similarly, an analytical solution for matrix flux potential distribution around a surface point source (ϕ_s) is given as (Raats, 1971; Revol et al., 1996):

$$\phi_s(r,z) = 2\phi_B + \frac{\alpha q e^{\alpha z}}{4\pi(r^2+z^2)^{0.5}} \mathrm{Ei}\left[-\frac{\alpha}{2}(z + (r^2+z^2)^{0.5})\right] \tag{6}$$

where ϕ_B is the matrix flux potential distribution around a buried point source, and Ei is the exponential integral. The primary difference between surface and buried source solutions stems from the geometry of the flow domain (infinite medium for buried vs. semi-infinite for the surface source). Consequently, for a given source strength (i.e. dripper flow rate) the wetting patterns from surface and buried sources will be different as shown for example in Figures 1 and 2 (see also Raats, 1971). The surface source solution (Equation (6)) does not consider the development of a small pond on the soil surface during infiltration as discussed by Revol et al. (1996).

For practical applications, one is interested in the distribution of h around either a surface or buried point source, this is obtained by the following transformation:

$$h(r,z) = \frac{1}{\alpha}\ln\left(\frac{\alpha\phi(r,z)}{K_s}\right) \tag{7}$$

The corresponding soil water content ($\phi(r, z)$) distribution can then be obtained via soil water retention models of Van Genuchten (1980) or Russo (1988).

Other multi-dimensional analytical solutions to Equation (1) have been provided by Gilley and Alfred (1974), Warrick et al. (1979) and Warrick et al. (1980). Several one-dimensional numerical solutions to Equation (1) have been provided over years (Feddes et al.,

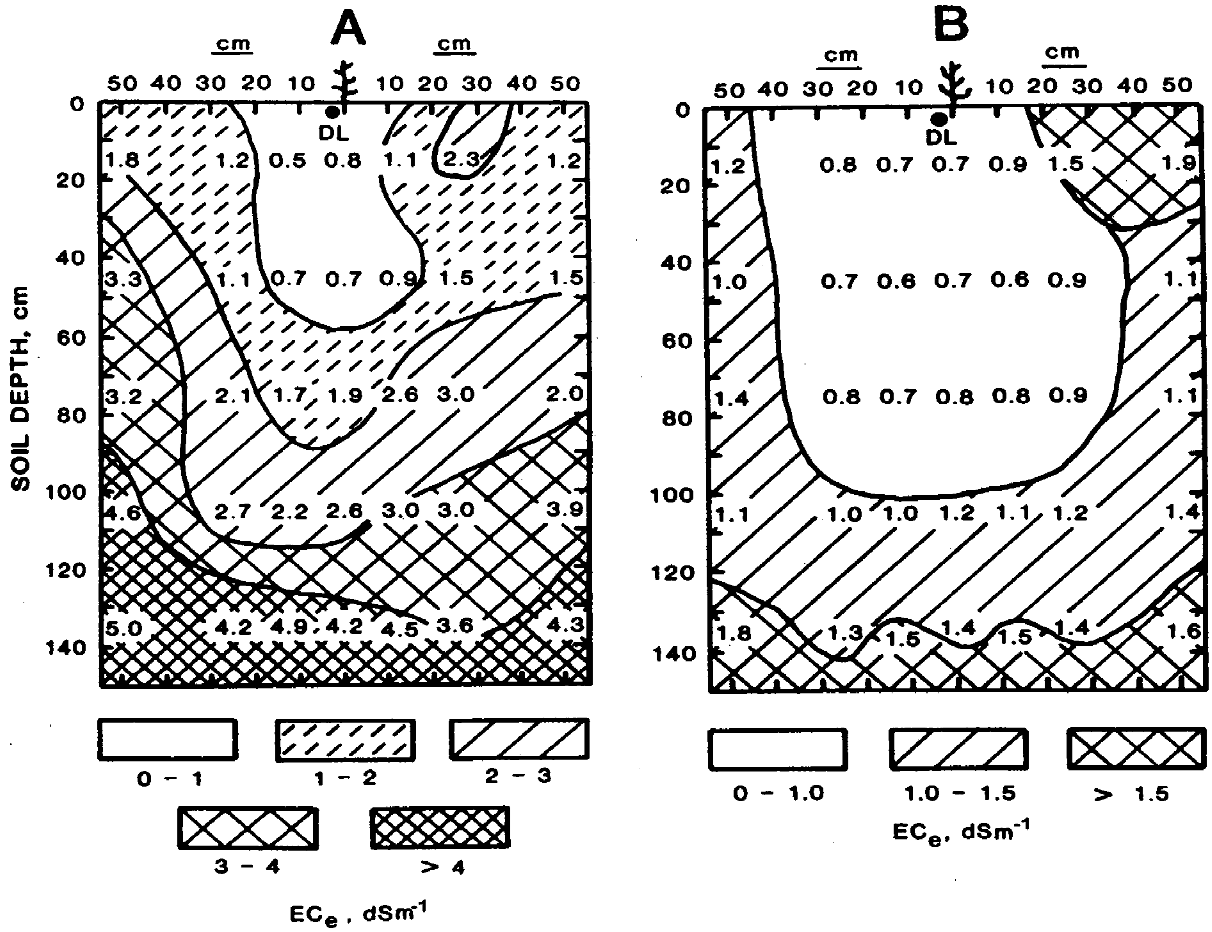

Figure 1. Distribution of ECe (dSm^{-1}) under drip irrigation, (a) 0 mm preplant irrigation and (b) 190 mm preplant irrigation (Source: Nightingale et al., 1986).

1974; Jung and Taylor, 1984; Nimah and Hanks, 1973; Ragab et al., 1990). Similarly multi-dimensional numerical solutions to Equation (1) have been provided by Clausnitzer and Hopmans (1994).

Solute transport modeling by the convection-dispersion equation (CDE)

Solute transport in the wetted soil volume is often described by the CDE that takes into account the three main mechanisms of solute transport, namely convection, diffusion and dispersion. In convective transport, solutes are carried by mass flow of water. Diffusive transport occurs as solutes diffuse from locations of higher solute concentration to lower concentrations. Because the soil has different sizes and shapes of pores, differences in pore velocities cause solutes to be transported at different rates to different locations. This leads to mixing of incoming solutes with resident concentrations and this phenomenon is referred to as hydrodynamic dispersion. These types of solute transport and their combinations have led to several formulations of models for predicting solute transport. Solute transport modeling approaches vary in their assumptions, complexity, as well as their data requirement, and acquisition. According to Jury (1984), field scale solute transport can generally be categorized into deterministic and stochastic models. Deterministic models use continuity equations with parameters having values at every point in space and having a fixed logical relation to each other. On the other hand, stochastic models use parameters that are assumed to vary randomly and may be characterized in terms of a probability distribution (Jury, 1984).

A multidimensional convection-dispersion equation for reactive solute in an anisotropic media is given

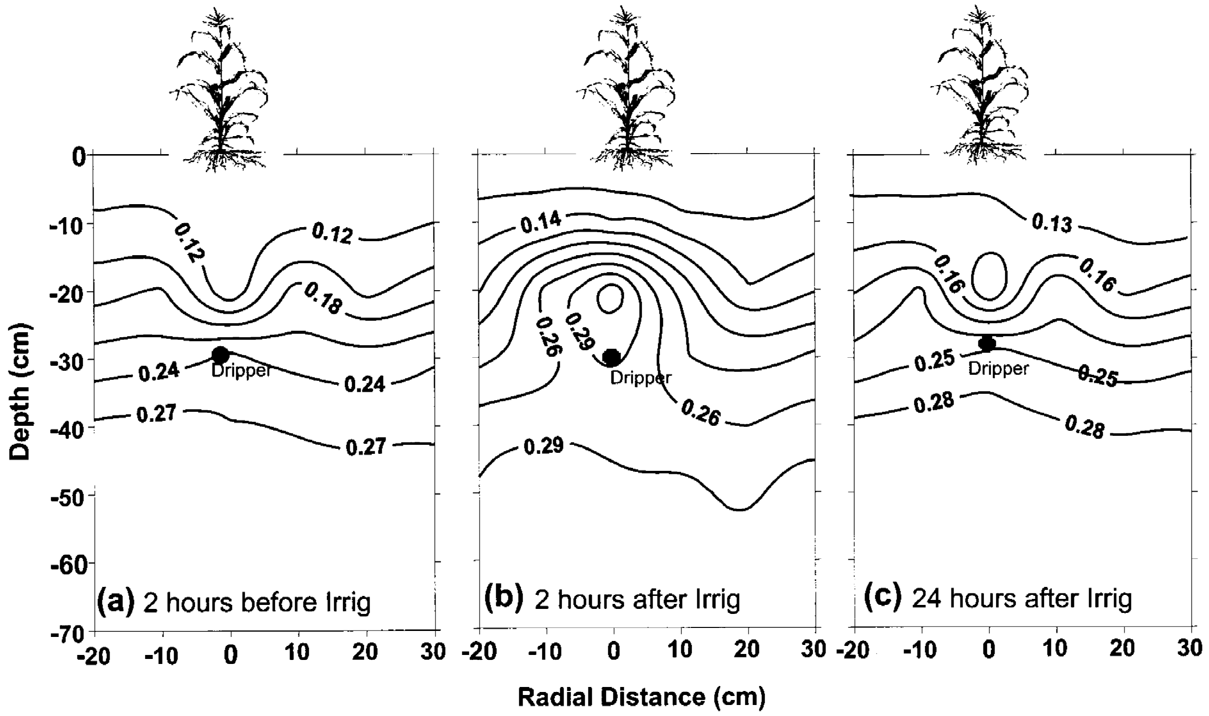

Figure 2. Temporal and spatial variations in volumetric soil water content distribution with time in soil rootzone of young corn plants 35 days after emergence in a greenhouse experiment. Subsurface dripper with flow rate of 1.6 L/h. (a) 2 hours before irrigation, (b) 2 hours after irrigation and (c) 24 hours after irrigation.

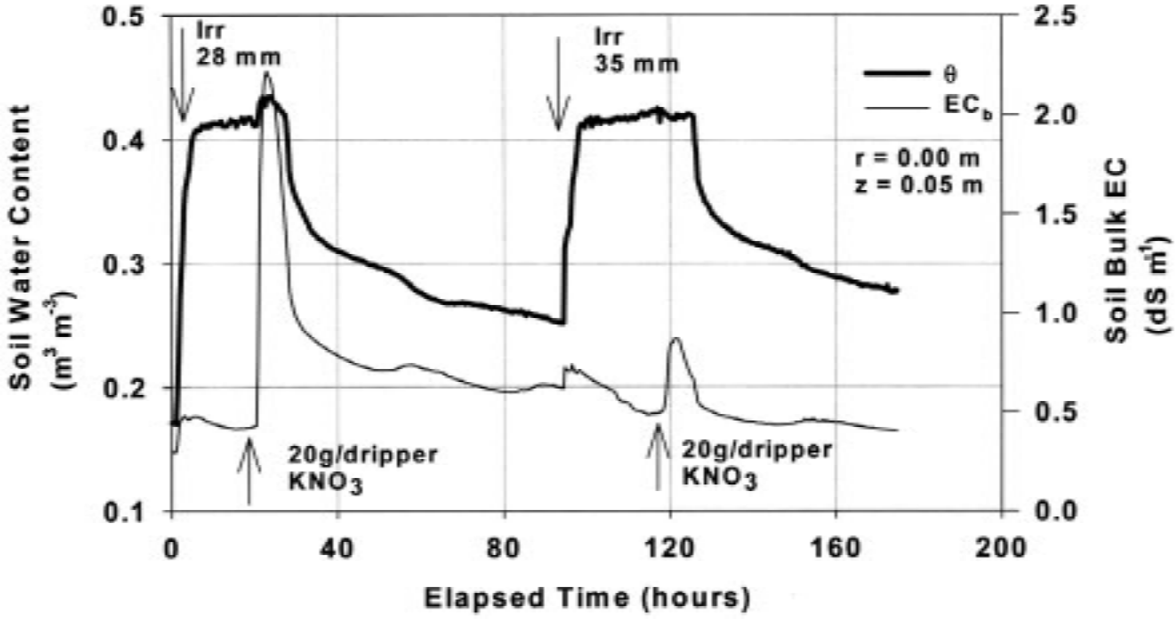

Figure 3. Dynamics of soil water content and soil bulk electrical conductivity for a given soil volume measured in a corn field with the dripper located on the surface of the crop row. The radial distance is r = 0.0 m, and the depth is z = 0.05 m, the dripper discharge is q = 1.6 L/h.

as (Van Genuchten and Alves, 1982):

$$\theta \frac{\partial C}{\partial t} = \theta \nabla (D \nabla C) - q \nabla C - p \frac{\partial S}{\partial t} - Q \qquad (8)$$

where C is the solute concentration (kg m^{-3}), ρ is the soil bulk density (kg m^{-3}), D is the solute dispersion

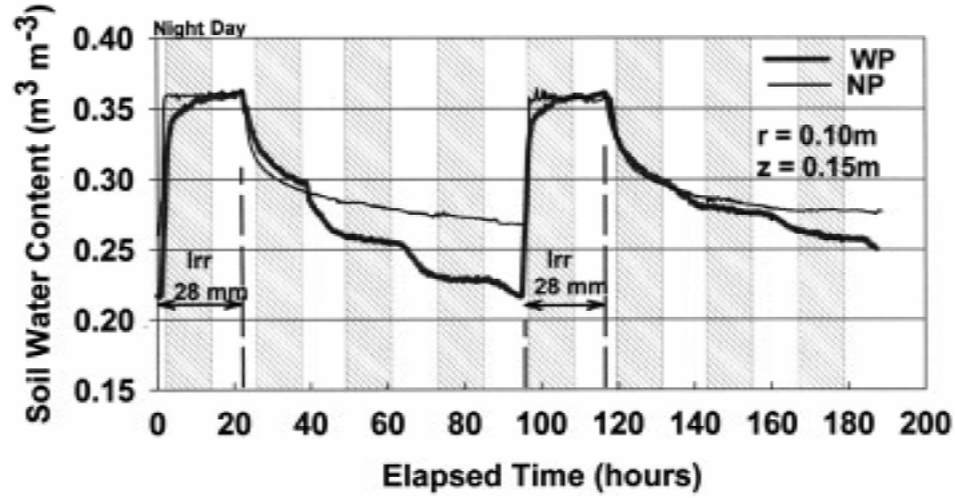

Figure 4. Temporal water content changes for a buried dripper beneath a crop row, with- (WP) and without-plants (NP). The radial distance is $r = 0.10$ m, and the depth is $z = 0.15$ m, the dripper discharge is $q = 1.6$ L/h.

coefficient ($m^2\ s^{-1}$), Q is a sink or source for irreversible solute interaction ($g\ m^{-3}\ s^{-1}$), t is time (s), q is the Darcy soil water flux ($m\ s^{-1}$), $\bigtriangledown$ is the spatial gradient operator, S is the amount of solute adsorbed to the soil matrix ($kg\ kg^{-1}$ of soil).

Numerical and analytical solutions for the convection dispersion equation

Equation (8) has been solved under different solute transport scenarios and assumptions (Bresler, 1975; Leij et al., 1991; Van Genuchten and Alves, 1982). For nonreactive solute transport in the absence of sources or sinks for the solute in the soil, Equation (8) is reduced to:

$$\theta \frac{\partial C}{\partial t} = \theta \bigtriangledown (D \bigtriangledown C) - q \bigtriangledown C \qquad (9)$$

A two-dimensional form of Equation (8) has been solved numerically by Tim and Mostaghimi (1989) to describe the transient phosphorous movement and distribution in the vadose area. Bresler (1975) has numerically solved Equation (9) in two dimensions. Numerical solutions for one-dimensional CDE have been provided (Moldrup et al., 1989; Shao et al., 1998). Equation (9) has been numerically solved without the retardation term (Bresler, 1973; Hillel et al., 1976). Similarly, analytical solutions have been provided for Equations (8) and (9) by several others (Gelhar and Collins, 1971; Leij and Dane, 1990; Leij et al., 1991; Van Genuchten and Alves, 1982).

Despite the simplifying assumptions in their development, analytical models are easy and simpler to handle than numerical models. But they are usually preferred over numerical models because, 1. they require fewer parameters both to describe and analyze problems, 2. there is direct relationship between input and output parameters, and 3. analytical models offer predictive capabilities whereas numerical models often apply only to the particular simulated case. These relationships can allow sensitivity analysis of the input and output analytical model parameters. According to Leij et al. (1991), analytical solutions can also become handy for extrapolating transport parameters over large distances and times when numerical models become less applicable.

Drip fertigation

Scheduling of fertigation

As plants grow, their demand for salts change, and as such, some salts that are easily taken up by plants may get depleted sooner than the excluded ones. This preferential uptake of solutes can lead to high concentrations of the excluded salts in the rhizosphere that could prove to be detrimental for optimum plant growth. Thus fertigation is often necessary to augment nutrient fertilizers. A fertigation scheduling plan is often compounded by the changing climatic conditions and the changing demands of fertilizer requirements of growing plants. Nevertheless, fertigation should be carried out, not to adversely alter the solute dynamics in the root zone, but should provide tolerant and

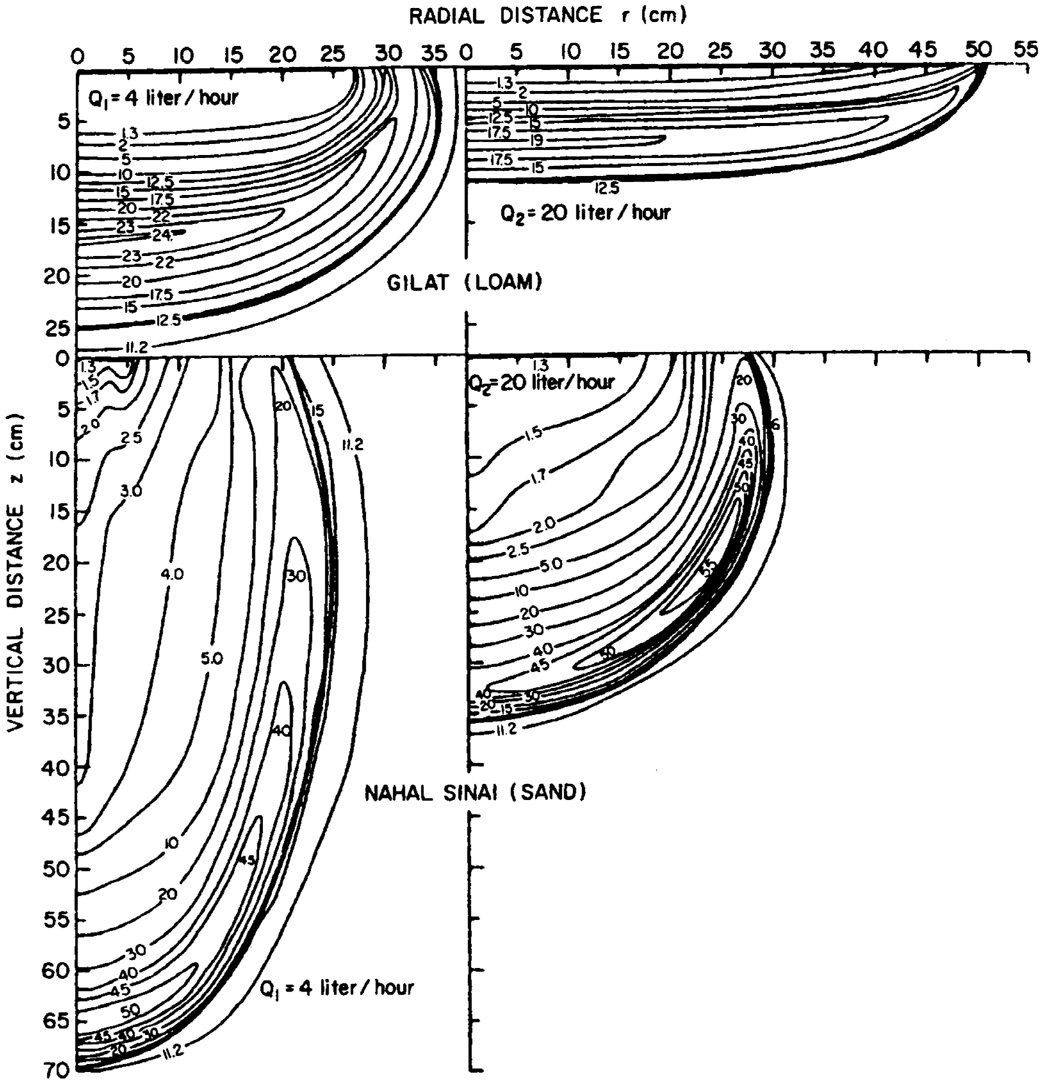

Figure 5. Distribution patterns for volumentric salt content for loam and sandy soil. Two different emitter discharges of 20 L/h and 4 L/h were used to illustrate volumetric salt content distribution (Source: Bresler, 1977).

optimum concentrations of nutrients and salts in the rhizosphere. Hence, accurate prediction of when and how much fertilizer to apply is critical for fertigation management. The amount of fertilizer to be applied depends on the plant requirement at the time of application. The frequency of application for fertilizers depends among other factors on the soil type, system design constraints, and the length of the growing season. According to Hochmuth (1992), the frequency of fertigation is usually not as critical as achieving the right rate of application at a given crop stage. Table 1 shows some fertigation schedules for mulched vegetables in Florida, with guidelines for fertilizer injection rates for nitrogen and potassium fertilizers.

Drip fertigation with N, P and K

The nutrient supply to crops through fertigation is a function of the concentration of nutrients in the irrigation water, the concentration of the soil solution, crop evapotranspiration (ET) and nutrient uptake by the plant. Detailed information on nutrient uptake by plants is fundamental to optimizing nutrient application (Hagin and Lowengart, 1996). Most crops need nitrogen (N) in relatively large amounts as compared to other plant nutrients (Hochmuth, 1994). For pur-

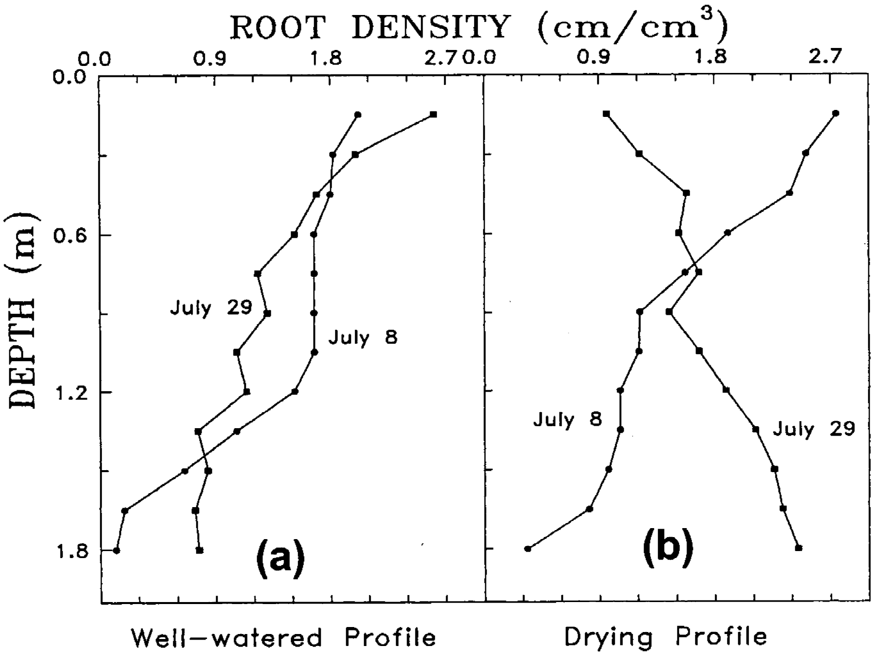

Figure 6. Root length density variation with depth over some period, July 8–July 29, (a) well-watered profile and (b) drying profile (Source: Klepper, 1991).

poses of a balanced review and discussion, drip fertigation will be discussed to include N fertigation, as well as other macronutrients, phosphorous and potassium fertilizers.

Usually the optimizing of N management with drip irrigation would require that attention be paid to soil N dynamics, crop N requirements, as well as soil and plant monitoring techniques (Hartz, 1993). Boswell et al. (1985) reported that nitrate–N is relatively unreactive and, therefore, susceptible to movement through diffusion and mass transport in the soil water because 1. nitrate compounds are readily soluble in water, and 2. they are not usually adsorbed on the negatively charged soil clay particles. Since nitrate–N is highly soluble and nonadsorbing, it is more likely to be lost through surface water runoff and deep percolation of water. Except when large amounts of fertilizers are surface applied first before heavy rainfall events, soluble N losses through surface runoff are generally small. There is usually more gain in N through rainfall events than is lost through surface runoff (Boswell et al., 1985). Gaseous N losses mostly involve denitrification and volatilization of ammonia. Denitrification is the process by which nitrates are converted to N gases through micro-organism activities in the soil. Leaching of N is probably the dominant way in which N is lost in the soil–plant system, especially if the soil already contains substantial amounts of nitrate–N. Although the background concentration of the nitrate–N plays a significant role in the overall loss of N beyond the rooting zone, the rate and timing of N fertilizers is also important in avoiding both excessive amounts of N or applying it unnecessarily.

The adsorption and precipitation processes that take place in the soil upon addition of phosphorous (P) lead to a rapid decline of water-soluble phosphorous with time. Since water soluble phosphorous reacts with the soil matrix, its concentration in the soil water solution is usually low and its movement is thus restricted and retarded. Consequently, phosphorous compounds are usually considered immobile and phosphorous runoff and leaching are considered insignificant (Feigen et al., 1990). Phosphorous application through drip irrigation is not commonly recommended, mainly because of 1. possibility of precipitation of phosphates, and 2. the low mobility of phosphates (Chase, 1985; Haynes, 1985; Mikkelsen, 1989; Rauschkolb et al., 1976; Mikkelsen and Jarrell, 1987).

Rauschkolb et al. (1976) found the same leaf content of P in tomato with the application of P through a drip irrigation system at 6.5 kg ha^{-1}, similar to a banded treatment of 26 kg ha^{-1}. Bar-Yosef et al. (1989) mention that increasing the concentration of applied P in the irrigation water from 0.04 mol m^{-3} to 1.29

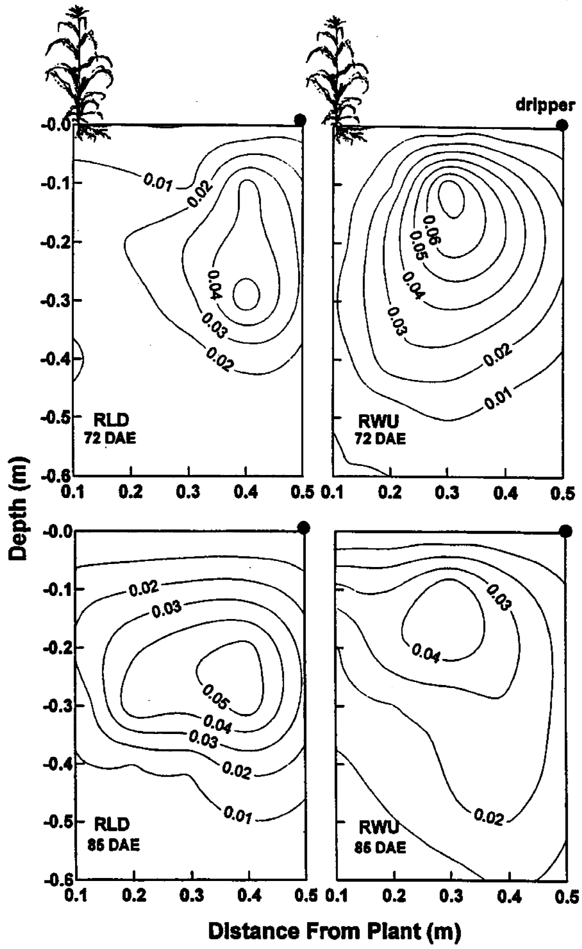

Figure 7. Normalized root length density (RLD) and root water uptake (RWU) values around a surface drip source placed between crop rows, 72 DAE (top) and 85 DAE (bottom) (Source: Coelho and Or, 1999).

mol m^{-3} for surface emitters increased sweet corn yields from about 22 tons per hectare to 26 tons per hectare. But for subsurface emitters they found that with the same concentration of P, the sweet corn yield went from 23 tons per hectare to 29 tons per hectare. According to Bar-Yosef (1999), subsurface fertigation ensures that nutrients are supplied to the center of the root system thereby improving their efficient use.

Potassium (K) fertilizers, when added to irrigation waters, do not generally cause any adverse chemical reactions that plug irrigation pipes and emitters. But they may well cause precipitation of insoluble salts if mixed with other fertilizers. For example, if calcium nitrate is mixed with K sulfate insoluble calcium sulfate will result (Rolston et al., 1986). The soil solution K is usually too low for adequate plant nutrition during any crop season. As a result, K has to be replenished through release of fixed K, exchangeable and structural K. But these K-replenishing processes may not guarantee sufficient K in the soil for optimum plant growth (Sparks and Huang, 1985).

Irrigation with water of marginal quality

Pratt and Suarez (1990) mention that if the assessment of the quality of irrigation water is to be meaningful, factors such as the chemical reactivity of constituents dissolved in the water, the soils chemical and physical properties, climate and irrigation management practices should all be considered. Irrigation water quality is based on three factors (Bar-Yosef, 1999; Hoffman, 1986) namely; (a) Salinity, the general effect of dissolved salts on crop growth that are associated with osmotic stress, (b) Sodicity, the effect of an excessive proportion of sodium that induces deterioration of soil

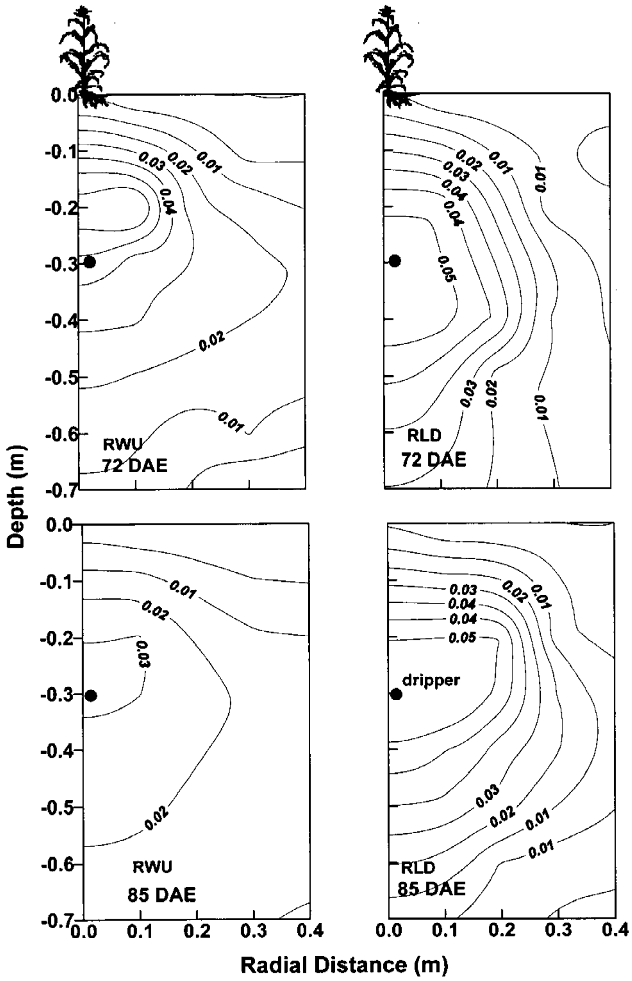

Figure 8. Normalized root length density (RLD) and root water uptake (RWU) values around a subsurface drip source buried under crop rows, 72 DAE (top) and 85 DAE (bottom) (Source: Coelho and Or, 1999).

permeability, and (c) Toxicity, effects of some specific solutes that damage plant tissue or cause imbalance in plant nutrition. But, Bar-Yosef (1999) adds that if municipal or recycled waters are to be used for irrigation purposes, then two additional quality criteria are used (d) BOD-biochemical oxygen demand, which is the quantity of oxygen required for microbial degradation of organic compounds in water at 20 °C, and (e) Total suspended solids in water. It is worth noting that these water quality criteria are not specific for drip irrigation.

Irrigation with saline water

If the irrigation water happens to contain high levels of dissolved sodium, then irrigating soils with such water would cause swelling and dispersion of soil clay particles. This swelling and dispersion of soil clay particles results in the reduction of pore sizes in the soil, and consequently the reduction of soil hydraulic conductivity, infiltration rate and destruction of soil structure. Feigen et al. (1990) have pointed out that the extent of the salinity effect depends on the exchangeable sodium ratio (ESR) and the electrical conductivity (EC) of the soil solution.

If the irrigation water contains large amounts of dissolved solutes, the bulk soil water solution concentration will be increased also. But due to the diffusion barrier created by plant roots, the osmotic potential of the bulk soil water solution will be lowered, making it difficult for plants to take up water. If the osmotic stress goes on for long periods unchecked, plants will wilt and die. If the irrigation water contains less dis-

Table 1. Fertigation schedules for some vegetables in Florida (adapted from Hochmuth (1992))

Crop	Total nutrition (Kg/ha)		Crop Development		Injection Rate (Kg/ha/day)	
	N	K	Stage	Weeks	N	K
			1	1	1.1	0.9
Cucumber	135	112	2	2	1.7	1.5
			3	6	2.2	1.9
			4	1	1.7	1.5
			1	2	1.7	1.5
Lettuce	135	112	2	1	2.2	1.9
			3	4	2.8	2.4
			4	1	2.2	1.9
			1	2	1.1	0.9
Pepper	179	149	2	3	1.7	1.5
			3	7	2.2	1.9
			4	1	1.7	1.5
			5	1	1.1	0.9
			1	2	1.1	0.9
Tomato	179	149	2	3	1.7	1.5
			3	7	2.2	1.9
			4	1	1.7	1.5
			5	1	1.1	0.9

Table 2. Seasonal average soil salinity (EC_e in dS m^{-1}) at different depths for two water quality treatments (adapted from Pasternak et al. (1995))

Water treatment	Depth (m) 0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
	ds/m			
Fresh water	2.6	1.8	1.4	1.9
Brackish water	6.5	5.3	4.8	5.5

solved solutes than the bulk soil water solution, then during the irrigation phase the root zone will be diluted and resident salts pushed to the root zone fringes. But after irrigation has stopped and plants take up water and evaporation takes place, then some salts will be left at the fringes leading to accumulation of salts at these locations.

When drip fertigating with P under saline water conditions, precautions should be taken not to increase the Sodium Adsorption Ratio (SAR) by either increasing Na^+ or greatly reducing Ca^{2+} and Mg^{2+} ions in soil solution, which will lead to soil deterioration of hydraulic and physical properties. Since N and K fertilizers are reasonably soluble, fertigation with them is likely to increase the cation exchange capacity (CEC) that decreases the ESR.

Boron, although essential for plant nutrient requirements, becomes toxic if its concentration in irrigation water exceeds 0.5–1.0 mg L^{-1}. Chloride is the most prevalent ion in irrigation waters. Its threshold concentration for causing damage varies with crops. Its side effects are usually more pronounced in woody perennial fruit trees. When sodium is in high concentrations in the saline irrigation water, it can impair uptake of calcium or K and subsequently lead to crop nutritional imbalance. But sodium toxicity may be specific to some crops in a similar way as chloride (Feigen et al., 1990).

Some aspects of brackish water irrigation

Pasternak et al. (1995), after investigating salt tolerance of corn cultivars using two water treatments (fresh and brackish water of 1.2 dS m^{-1} and 6.2 dS m^{-1}, respectively), found that by the end of the season most salts had accumulated at the top 30 cm depth, where most roots are found under drip irrigation. But surface evaporation of water must have also contributed to the shifting of the peak salinities at the top 30 cm depth (see Table 2).

When tomatoes were germinated with fresh water and then irrigated with brackish water with an EC of 7.5 dS m^{-1}, the fruit yield was reduced by 30% 30 days after emergence. However, if the 7.5 dS m^{-1} brackish water was applied at emergence, the fruit yield was decreased by 60% (Pasternak et al., 1986).

Daily irrigation frequency with brackish water was found by Ayars et al. (1985) to result in lower average salinity profiles, compared to a 3–4 day irrigation frequency. Pasternak and Malach (1995) found that under high evaporative conditions in the Negev highlands of Israel during summer, tomato plants grown on sandy soils were affected more by brackish water irrigation than those growing on heavier soils. They also found that an irrigation frequency of five times a day (pulse irrigation) with brackish water leaches salts from the root surfaces and releases salt stress, with a resulting increase in yield. Although brackish water irrigation tripled the sodium concentration in tomato leaves, the amount of K and P in the tomato leaves was decreased, which indicates that K and P elements might become deficient under brackish water irrigation.

In contrast to Ayars et al. (1985), Shalhevet (1992) mentioned that the bulk evidence in the literature shows no advantage to increasing irrigation frequency when irrigating with brackish water. The major reason for his counteractive statement is that as irrigation frequency with brackish water increases, the evaporation component of the ET is increased, leading to additional water application and subsequent increase in the overall salt load.

Irrigation with municipal wastewater

Treated municipal wastewater is capable of reaching high quality water standards where the waste treatment technology is advanced. Usually the suitability of the water for reuse depends on the chemical composition of the source water and the extent of wastewater treatment. The chemical composition of treated wastewater effluents, although they vary, is generally acceptable if compared to the existing water quality criteria for irrigation water. But the treated wastewater effluents contain significantly higher amounts of N and P (Page, 1996). In addition to major plant nutrients, sewage effluent contains organic matter and trace elements. But unlike commercial fertilizers whose nutrient components can be tailored to suit crop requirements, plant nutrients and salts in sewage effluents are not controlled. Thus, application of wastewater effluent to supply one nutrient may lead to either excess application or negligible application of another nutrient (Page, 1996).

Characteristics of nutrient movement and distribution under drip irrigation

Despite the widespread use of fertigation with drip irrigation, only meager data are available on the simultaneous movement of water and dissolved solids from point sources (Clothier and Sauer, 1988). Inherent to drip irrigation is the water content distribution pattern around the emitter, resulting in a build up of salts at the fringes of the wetted soil volume. This phenomena has often led to a salt build up in drip irrigated fields and usually requires off-season leaching, especially if the irrigation water used contains considerable amounts of salts. Plant roots growing in the vicinity of the point source can modify this scenario, as they can intercept and take up water and salts applied (Green and Clothier, 1995; Gamier et al., 1986; Hamza and Alymore, 1992).

Experiments on water and solute movement and distribution

The influence of the amount of irrigation water applied on the solute distribution can be illustrated by the trickle irrigation experiments of Nightingale et al. (1986). They investigated the effect of the amount of preplant irrigation on the subsequent distribution of soil salinity for drip-irrigated cotton. As Figure 1 shows, a preplant irrigation of 190 mm led to a large reduction in the soil salinity at the end of the season, as compared to the no preplant irrigation.

We have conducted field and greenhouse experiments to investigate and elucidate temporal and spatial solute dynamics (Mmolawa, 2000; Mmolawa and Or, 2000). Time domain reflectometry (TDR) probes were used to simultaneously monitor spatial and temporal variation in soil water content (θ) and soil water solution bulk electrical conductivity (EC_b). The details of the relationship between θ, EC_b, and soil water solution concentration (C) can be found in the 'Appendix'. The monitoring of soil water content and EC_b was conducted with plants actively growing in the root zone, as well as when plants were removed. Figure 2 shows the two-dimensional distribution of θ with time from a greenhouse experiment with a 1.6 L h^{-1} dripper buried 0.3 m below soil surface, and directly underneath the corn plant row. Figure 2 also shows a high level of symmetry 0.2 m either way from the vertical axis at r = 0 m. Just 2 h before (Figure 2a) and 24 h after (Figure 2c) irrigation, the top 0.20 m of the soil profile is dry compared to the rest of the profile, particularly along where the plant is growing. The trough of low water content that develops 2 h before and 24 h after irrigation demonstrates root water uptake near the dripper, where there is sufficient moisture available. According to Figure 2b, shortly after irrigation, the highest water is around the dripper; it is, however, skewed upward because of gradients created by plant roots as they take up water. Figure 2 as a whole shows that there is a net movement of water downwards, although there was no drainage recorded. Noticeable soil water content dynamics of Figure 2 are mainly at the top 0.3 m of the soil profile because the corn plant is still young (35 days after emergence, DAE). Figure 3 depicts typical simultaneous temporal changes in θ and EC_b over a period of about 175 h at a fixed point in the root zone. In this case, the TDR probe monitoring the changes in θ and EC_b was located 0.05 m below a surface dripper placed between crop rows. The EC_b and θ changes can be converted to soil water solution concentration changes by using the relationships shown in the 'Appendix'.

As already mentioned, EC_b and θ changes were observed for both the no plants (NP) scenario and with plants (WP) scenario. When plants are present in the root zone, θ drops to lower values in between irrigations when compared to the NP situation (Figure 4). This difference in θ is attributed to plant uptake of water at the particular observation location. Figure 4 illustrates temporal fluctuations of water content for a buried dripper under a crop row in a drip-irrigated cornfield. The water content fluctuations are for a TDR probe located next to a buried dripper (r = 0.10 m, z = 0.15 m) for both WP and NP scenarios. A close look at the WP curve shows that there is a larger water content decrease during the daytime interval than during the nighttime. For the NP curve, the water content decrease is smooth and gradual, irrespective of the day or nighttime.

Modeling water and solute dynamics under drip irrigation (no plants)

Bresler (1977) computed and compared volumetric salt content for two soils with two different texture characteristics and emitter discharges. The two soils had the same initial volumetric salt content for a given volume of soil, and the same amount of volumetric salt was added to them so that the difference in the dynamics of salts was due to the difference in the individual soil hydraulic properties. As Figure 5 shows, the soil type and the discharge rate of emitters influence the distribution of volumetric salt content. For the Gilat loam, under an emitter discharge of 20 L h^{-1}, the salts move greater distances laterally (r = 0.50 m) than vertically downward (z = 0.10 m). But for the Nahal Sinai sandy soil under the same flow rate, the lateral movement of salts is about half of the loam soil scenario (r = 0.30 m) and the downward move is three times (z = 0.35 m) that under the loam soil. When the emitter discharge is lower (4 L h^{-1}), salts move further down the profile in sandy soils (z = 0.70 m) than in loam soils (z = 0.30 m), but the lateral movement of salts in this case is almost the same (r = 0.35 m for loam soil and r = 0.25 in for the sandy soil).

Root distribution

Spatial distribution of plant roots is an integral part of water extraction functions or models. Root systems can be expressed in several ways, such as root percentage distribution, root density distribution and root length density (RLD) distribution. Phene et al. (1991) explained that it is especially important in drip irrigation to define these root parameters, since it is widely believed that drip irrigation may limit the wetted soil volume and, therefore, the extent of root development. But root distributions have been found to depend mostly on the availability of the water, type of irrigation system, crops and soils (Kamara et al., 1991; Phene et al., 1991; Zhang et al., 1996).

According to Molz (1971), an important variable in any study of root water uptake is the physical distribution of roots, which can be expressed as root length per unit volume of soil (m m^{-3}) or mass of roots per unit mass of soil (kg kg^{-1}). But he does acknowledge that the relationship between the root distribution and uptake is complicated by the fact that the volume or mass of roots in a given location does not necessarily reflect the ability to absorb water. Pages et al. (1989) contend that in order to develop models for soil plant systems, it is important to describe the spatial distribution of roots over time.

Another major problem usually encountered in any attempt to describe accurately the soil water uptake by plant roots is complicated by the inherently complex space and time relationship involved (Clothier and Green, 1997). This is because roots grow in different directions, spacing, at different rates and even show sectional differences in uptake, depending upon age and location (Hillel et al., 1976). This disorderedly proliferation of root systems could result in disparity between RLD and actual root water and solute uptake. Hence, root water and solute uptake models based on RLD are destine to fail when there is large disparity between the RLD and actual root uptake of water and solutes (Clothier et al., 1990; Coelho and Or, 1999).

Root distribution and parametric models

In their derivation of a model for root system distribution Gerwitz and Page (1974) presented the following equation to express the percentage of roots in a given soil horizon in one dimension as:

$$\frac{dP}{dx} = e^{-fx+c} \qquad (10)$$

where dP is the percentage of roots within a soil horizon of thickness dx at a depth of x (m), and f and c are empirical constants. Equation (10) can be simplified to represent percentage of roots between the surface and any depth x as:

$$P = 100(1) = \mathrm{e}^{-fx} \tag{11}$$

Zhang et al. (1993) developed one- and two-dimensional models for describing spatial distributions of peanut roots. They used RLD under different water treatments to model the root distribution. Working under the assumption that root length density is an indicator of root water activity, they formulated both linear and exponential forms of root length density for one- and two-dimensional cases. The following equations were used to model RLD distribution (Zhang et al., 1993):

(a) Linear approach:

$$r(x, z) = \frac{C_1(2Z - Z_r) + C_2(2X - X_r) + Z_r}{X_r} \tag{12}$$

with:

$$C_1 = -\frac{\beta_1 Z_r}{2\beta_0 - \beta_1 Z_r - \beta_2 X_r} \tag{13}$$

and:

$$C_2 = -\frac{\beta_2 Z_r}{2\beta_0 - \beta_1 Z_r - \beta_2 X_r} \tag{14}$$

(b) Exponential approach:

$$r(x, z) = \alpha \exp(-\beta_1 Z) \exp(-\beta_2 X) \tag{15}$$

with:

$$\alpha = \frac{\beta_2 \beta_1}{[1 - \exp(-\beta_1 Z_r)][1 - \exp(-\beta_2 X_r)]} \tag{16}$$

where x is the row spacing (m), Z_r is the rooting depth (m), X_r is the one-half row spacing (m), β_0, β_1, β_2 are empirical constants. They concluded from their experiments that the exponential forms of the RLD models fitted the observed data better than the linear approach models.

Acock and Pachepsky (1996) developed a two dimensional convective-diffusive root system model in which the proliferation and growth of roots in all directions is viewed as a result of diffusion-like gradient, whereas the convection-like propagation of roots downward is perceived to be caused by geotropism. After using Chen and Lieth's (1993) experimental data to test their convective-diffusive model, Acock and Pachepsky (1996) found that it was not necessary to relate root diffusivity to root density, that potential root growth increased linearly with root density, and there was no geotropic trend in root development.

Root distribution and root water uptake patterns

Chandra and Rai (1996) have mentioned that many studies suggest that root water uptake is related to the root density and that root water uptake varies non-linearly with depth in the soil profile. According to Hayhoe (1981), root distribution is a critical factor in influencing soil water uptake by a crop. Although root distribution is a highly dynamic process, Ehlers et al. (1991) assumed steady state conditions for their development of a model linking root density and water uptake. If soils are frequently irrigated, especially from the surface, they will remain relatively wet there and most of the root water uptake will then take place in the upper soil layers (Klepper, 1991). Figure 6 shows the contrast on distribution of RLD for well-watered and drying soil profiles of growing cotton. It can be seen from Figure 6a that as the soil profile was frequently watered between July 8 and July 29, the root density did not change except that it remained high at the upper soil profile. But Figure 6b shows that for the same period in the drying profile, RLD distribution was actually reversed during this period. As the soil dried at the surface and top profile, extraction of water will take place at the deeper profile, and this is what Figure 6b depicts. Recently, Coelho and Or (1999) have characterized a two-dimensional root distribution for drip irrigated corn plants. They fitted Gaussian distribution parametric models they had earlier developed (Coelho and Or, 1996) to the corn RLD to produce two-dimensional root distributions that they compared to root water uptake (RWU) patterns as shown by Figures 7 and 8. Although it has been shown that the actual water uptake patterns are a result of complex interplay between RLD and other soil factors, such as water and nutrients, the distribution of RLD is still an important indicator of potential water uptake. But flexibility and plasticity of root systems, infrequent irrigations and variations in wetting patterns can result in disparity between the RLD pattern and the actual RWU pattern (Coelho and Or, 1999). The two dimensional parametric model for RLD (or RWU) distribution for a buried drip source on a crop row, for example, is (Coelho and Or, 1999):

$$\mathrm{RLD}^*(r, z) = \frac{\beta}{2\pi s_r s_z} \exp \left\{-0.5 \left[\frac{(r - m_r)^2}{s_r^2} + \frac{(z - m_z)^2}{s_z^2}\right]\right\} \tag{17}$$

where RLD* (r, z) is the fraction of the total RLD at any given point (r, z), m_r and s_r are the mean and standard deviation, respectively, of RLD in the radial direction, m_z and s_z are the mean and standard deviation, respectively, in the z direction and, β is a scaling parameter. From Figures 7 and 8 it can be seen that there is stronger similarity between RWU and RLD distributions in Figure 8 than is the case of Figure 7. According to Coelho and Or (1999), a higher level of symmetry of the RLD and RWU for the buried dripper beneath the crop row (Figure 8) is expected than when a dripper is placed in between plant rows. This is because RLD and RWU patterns reflect the combined effects of distance from plant and non-uniform water availability within the wetted soil volume.

Modeling plant uptake of water and solutes

Models for water and solute uptake by roots

Modeling root water uptake is done at macroscopic and microscopic levels. With the macroscopic scale, the root system is usually represented by a volumetric sink term that is added to the continuity equation (Feddes et al., 1974; Hillel et al., 1976). The macroscopic approach ignores flow patterns towards individual roots and thus avoids the geometric complications involved in considering distribution of fluxes and potential gradients to individual roots. But the main disadvantage of this approach is that it is based on gross spatial averaging of the matric and osmotic potentials and, therefore, disregards the increase in suction and salt concentrations in the close vicinity of the absorbing roots (Clothier and Green, 1997; Hillel et al., 1976).

Macroscopic models are numerous in literature and were comprehensively reviewed by Molz (1981) and later by Alaerts et al. (1985) who compared the performance of some models. In most cases the important difference between these various models is the way in which the root water uptake term was derived (Tollner and Molz, 1983), or as Cardon and Letey (1992) put it, the uniqueness of each model depends on its formulation.

Although the macroscopic approach is more convenient to model root water uptake, it does not help to increase the understanding of water uptake by plant root, as the microscopic approach does, (Aura, 1996; Gardner, 1960). For the microscopic approach (see Figure 9), a single root is considered as a cylinder that is taken as a line source of uniform thickness and infinite length, having uniform water absorbing properties (Aura, 1996; Feddes et al., 1974; Herkelrath et al., 1977; Hillel et al., 1976; Radcliffe et al., 1986). The flow to the root is usually assumed radial (Clothier and Green, 1997; Gardner, 1960) and gravity is ignored (a notable exception is the model of Kirkham (1983) where gravity is explicitly considered).

Plant uptake of water and solutes is perhaps the most difficult to quantify as far as root zone solute and soil water dynamics are concerned. Most, if not all, of the uptake models that exist, contain parameters for uptake that have to be adjusted for a specific crop and for the specific conditions under which it is growing.

Macroscopic root water and solute uptake models

A further look into the macroscopic root water and solute uptake models reveals that they broadly fall into two categories. There are those that are derived considering root resistances, water potentials inside and at the root–soil water interface. These models have come to be regarded or known as potential flow theory models. According to Zhang and Elliott (1996), the success of these so-called potential flow theory models depends to a great extent on the accuracy of the determination of the root resistances and water potentials in and at the root interfaces. Examples of these potential flow theory models are those developed by Nimah and Hanks (1973), Protopapas and Bras (1987) and Marino and Tracy (1988). The rate of water extraction for these water potential flow theory models generally takes the form provided by Hillel et al. (1976) and Gardner (1990):

$$S = \frac{h_\mathrm{p} - h_\mathrm{w}}{R_\mathrm{r} + R_\mathrm{s}} \tag{18}$$

where S is the volumetric rate of water extraction by roots ($\mathrm{m^3\ m^{-3}\ s^{-1}}$), h_p is the plant water potential (m), h_w is the soil water potential (m) and, R_r the hydraulic resistances of roots ($\mathrm{s\ m^{-1}}$), R_s is the soil hydraulic resistance ($\mathrm{s\ m^{-1}}$).

Another group of the macroscopic root water uptake models is the one whereby the rate of water extraction by roots is equated to the plant transpiration rate. The argument for this idea has been that if plant ET is known, then the soil surface evaporation component can be subtracted from ET and the remaining transpiration part of ET apportioned to the root water uptake. Since the transpiration rate for plants depends on the roots and their activities, it is imperative that any uptake term derived on the principle of equating transpiration rate to root water uptake will be a function of root depth and water content or some combination of these.

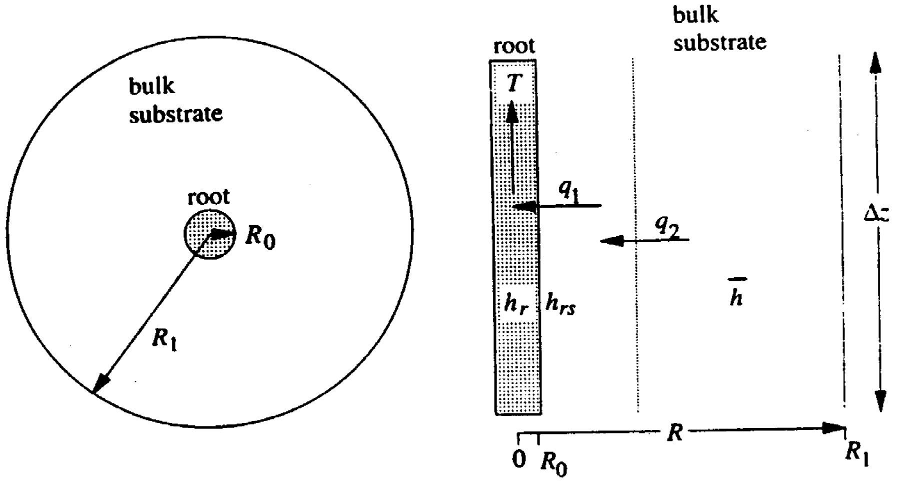

Figure 9. An illustration of microscopic uptake with a single root of radius R_0 surrounded by bulk substrate of radius R_1 (Source: Heinan, 1997).

With the apportioned transpiration modeling approach of root water uptake, usually a known transpiration rate for unit surface area is divided per soil layer. The root water uptake in one dimension then takes the form (Zhang and Elliott, 1996):

$$S = T_r F_w(r, K, D, h) \tag{19}$$

where S is the rate of root water uptake (m^3 m^{-3} s^{-1}), T_r is the transpiration rate per unit soil surface area (m s^{-1}), F_w is the weighting function (s^{-1}), K is the soil water conductivity (m s^{-1}), D is the soil water diffusivity (m^2 s^{-1}), h is the soil water potential (m). Molz and Remson (1970) expressed the general one-dimensional extraction term based on the apportioning of transpiration as:

$$S = S\left(z, t, \theta, \frac{\partial \theta}{\partial z}\right) \tag{20}$$

where S is the water extraction term (m^3 m^{-3} s^{-1}), z is depth (m), t is time (s), and θ is the water content (m^3 m^{-3}).

Microscopic root water and solute uptake models
Gardner (1960), Hillel et al. (1976), Herkelrath et al. (1977), Radcliffe et al. (1986), Aura (1996) and Heinen (1997) have presented the microscopic root water uptake by way of Figure 9. Firstly, the rate (q_2) of water movement from the bulk soil solution towards the individual root surface is equated to the rate of root uptake (q_1). The next step is to relate the RLD to the bulk soil solution with radius, R_1, around a root as:

$$R_1 = (\sqrt{\pi \mathrm{RLD}})^{-1} \tag{21}$$

Then the rate of root water uptake (q) by roots from a layer of thickness ΔZ with a known RLD (Heinen, 1997) can be defined is:

$$q = \Delta Z \cdot \mathrm{RLD} \cdot K_r(h_{rs} - h_r) \tag{22}$$

where K_r is the root hydraulic conductance (m s^{-1}), h_r is the root pressure head assumed uniform over the whole root system, and h_{rs} is the pressure head at the root- bulk soil solution interface (m).

Root uptake of nutrients

The amount of nutrients that can be absorbed by a plant depends on the availability of the nutrients in the soil. But the nutrient availability depends on the positional and chemical availability of the nutrient. The chemical availability is governed by the chemical bond and concentration of the nutrient in the soil solution, whereas the positional aspect is mainly determined by the mobility of the nutrients in the soil (Jungk, 1996).

Some nutrients are bound to the soil solid phase (reactive solutes) and thus are virtually immobile. Even those nutrients that are dissolved in the soil solution are not very mobile because they are entrapped in the water filled fraction of the tortuous pore system of the soil. Thus, nutrient transport through the soil is usually limited to low flow rates and short distances. Because the concentration of most nutrients in the soil solution is low, the kinetics of uptake of nutrients by plants becomes fundamental. The process of nutrient uptake from the soil to plant depends on the concentration of the nutrient at the root surface and the kinetics of uptake. The contact between the

Table 3. Significance of root interception, mass flow and diffusion in supplying maize with nutrients (kg/ha) (adapted from Jungk (1996))

	Amount required [a]	Approximate amounts supplied by each process ————-(kg ha^{-1})————-		
Nutrient		Root interception	Mass flow	Diffusion
Nitrogen	190	2	150	38
Phosphorus	40	1	2	37
Potassium	195	4	35	156

[a] For grain yield of 9500 kg ha^{-1}.

Table 4. Michaelis–Menten paramters for corn uptake of N, P and K (adapted from Barber (1985))

Crop	Nutrient	$I_{\max}$ (nmol m^2 s^{-1})	K_{m} (μmol L^{-1})	$C_{I\,\min}$ (μmol L^{-1})	I_n (nmol m^2 s^{-1})
Corn	$NO_3{}^-$	100	18	4	50
	P	40	3	0.2	20
	K	400	16	1	200

root surface and soil nutrients needed for uptake to occur can be brought about by either roots growing to sites where the nutrients are located, which is called root interception, or by transport of nutrients from the bulk of soil to the root surface. Diffusion is the major process for supplying the nutrients that are in the soil solution in different concentrations relative to the plant requirement (Jungk, 1996). But mass flow or convective transport is the dominant process by which nutrients are transported to plant roots (De Willigen and Van Noordwijk, 1994). Hence, any amount of nutrients supplied to the roots by mass flow can be estimated by multiplying the volume of plant-transpired water by the mean concentration of the nutrient in the equilibrium soil solution.

Table 3 shows that most of the N, which is a macronutrient, is supplied to maize (corn) roots by mass flow, with P and K being supplied mostly by diffusion. According to Jungk (1996), the mass flow of N may vary widely depending on the fertilizer level and the source, as well as the ammonium or nitrate ions taken up. Nitrate is usually more readily moved by mass flow than ammonium.

Solute uptake and nutrient concentration considerations

High transpiration rates can cause large flux of nutrients towards the root, and rapid accumulation of nutrients at the soil–root interface may lead to high and detrimental nutrient concentrations around the root zone. If these nutrients are excluded by the root, then the osmotic potential close to the root surface can become an exponential function of water uptake, and this could reduce water uptake if the salt concentration in the soil solution is so high as to lower the soil water potential close to the root surface (Hamza and Alymore, 1992).

According to Bar-Yosef (1999), root concentration distribution in the soil and nutrient concentration distribution in the soil solution are two important functions to be adjusted, such that plant uptake of nutrients is optimized. The overall net nutrient influx into the plant roots, I_n, usually follows the form of the Michaelis-Menten equation (Barber, 1985; Jungk, 1996; Mengel and Barber, 1974):

$$I_n = \frac{I_{\max}(C_I - C_{I\,\min})}{K_{\mathrm{m}} + (C_I - C_{I\,\min})} \quad (23)$$

or (Bar-Yosef, 1999):

$$I_n = \frac{I_{\max} C_r}{K_{\mathrm{m}} + C_r} \quad (24)$$

where $I_{\max}$ is the maximum net influx (pmol m^{-1} s^{-1}), C_I (mmol m^{-3}) is the soil solution concentration at the root surface, $C_{I\,\min}$ (mmol m^{-3}) is the soil solution concentration when the net influx is zero, C_r (mmol m^{-3}) is the nutrient concentration in the soil solution at the root surface, K_{m} is the Michaelis constant (mmol m^{-3}) and it is the value of (C_I–$C_{I\,\min}$) when I_n = 0.5 $I_{\max}$.

The integration of Equation (23) or (24) over the entire rooting zone forms the basis for calculating nutrient uptake with plant growth for a number of nutrient uptake simulation models. But when nutrients accumulate within the root, the internal root concentration (C_{pl}) may affect I_n, and thus in those cases, Equation (24) is replaced by:

$$I_n = I_T(C_r - C_{\mathrm{pl}}) \quad (25)$$

where I_T (cm s^{-1}) is the root ion transfer constant (Bar-Yosef, 1999). Table 5 shows the $I_{\max}$, K_m and $C_{I\,\min}$ values for N, P and K for a corn crop. Similar values are also provided by Bar-Yosef (1999).

To be able to estimate plant uptake by integration of Equation (24), there is a need to know the concentration C_r. But solving an Equation describing the

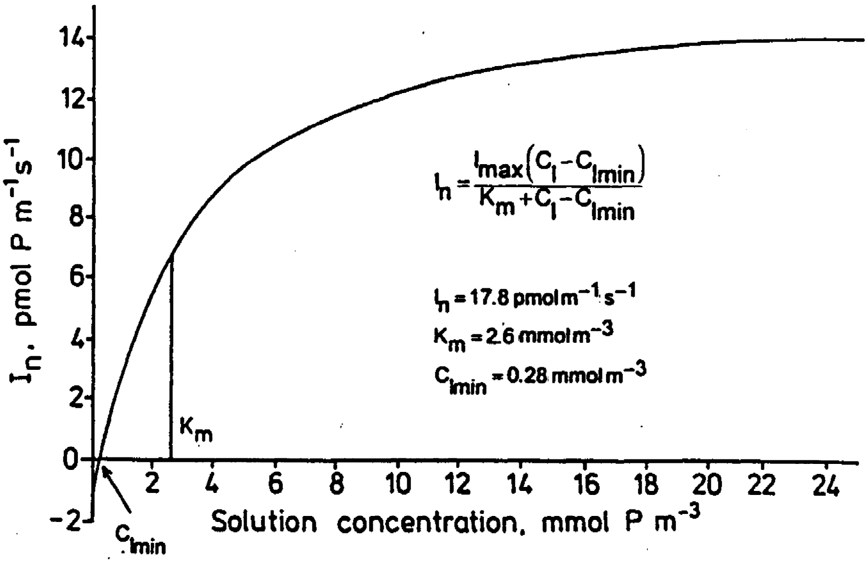

Figure 10. Depiction of the relationship between I_n and other Michaelis-Menten constant for phosphorus (Source Barber, 1985).

Table 5. Calculated corn uptake rates of N, P and K as related to plant age and mean root length per plant. For nutrient uptake in micro moles per day per plant, column 2 should be multiplied by column 5 (adapted from Mengel and Barber (1974))

Corn age (days)	N	P	K	Mean root length (m)
	μmol m^{-1} d^{-1}			
20	26.90	11.30	52.90	4
30	32.40	0.90	12.40	110
40	18.50	0.86	8.00	618
50	11.20	0.66	4.75	1242
60	5.70	0.37	1.63	1858
70	1.20	0.17	0.15	2409
80	0.46	0.08	0.06	2790
90	2.00	0.10	0.37	2680
100	4.20	0.23	0.16	1580

transport of ions from the bulk soil to the root surface can approximate C_r. The governing Equation for microscopic radial flow to an individual cylindrical root under steady state flow is (Bar-Yosef, 1999):

$$[b(C)+\theta]\frac{\partial C}{\partial t} = \frac{\partial}{\partial r}\left(D_p\frac{\partial C}{\partial r}\right) + \frac{1}{r}\left(D_p\frac{\partial C}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial r}(q_0 r_0 C) \quad (26)$$

where q_0 (m s^{-1}) is soil solution velocity at the root surface, r_0 (m) is root radius, and D_p (m^2 s) is the diffusion coefficient in the soil solution. According to Bar-Yosef (1999), the boundary conditions that suit the fertigation principles concerning Equation (24) can be used for solving Equation (26), as follows:

$$-D_p\frac{\partial C}{\partial r} + q_0 C = \frac{I_{\max} C_r}{K_m + C_r} \quad (27)$$

The outer boundary condition, found either at the edge of the root-affected soil volume or midway between adjacent roots, whichever is smaller, (at $r=R$), is:

$$\frac{\partial C_R}{\partial r} = 0 \quad (28)$$

Then the steady state solution of Equation (26) subject to boundary conditions 27 and 28, is given by (Bar-Yosef, 1999):

$$C_r = \frac{I_{\max}}{W\left(\frac{K_m}{C_r}+1\right)} + \left[C_R - \frac{I_{\max}}{W\left(\frac{K_m}{C_r}+1\right)}\right]\left(\frac{R}{r_0}\right)^{\frac{w}{2\pi D_p}} \quad (29)$$

where:

$$W = q_0 2\pi r_0 \theta \quad (30)$$

Then, Equations (24) and (29) are usually used to derive some threshold nutrient concentration in irrigation water. When C_r is greater than K_m the increase in I_n due to C_r diminishes quickly. It is, therefore, not advisable to maintain soil solution concentrations at

Table 6. Nitrate N uptake by corn plant in the field, 86 to 89 DAE, from TDR measurements. Values are for observation location close to a dripper on crop row and buried at a depth of 0.25 m below the surface

R	Z	Plant uptake	Upscaling to
(m)		(g_{KNO3} d^{-1})	the entire grid (g_{NO3-N} m^{-2} d^{-1} per plant)
0	0.15	0.018 (0.0087)[a]	0.20
0	0.25	0.022 (0.0087)	0.24
10	0.25	0.026 (0.0087)	0.27
0	0.35	0.065 (0.0074)	0.71
0	0.45	0.096 (0.0043)	1.06
Mean			0.50

[a]Temporal change in mass in the absence of plants.

the root surface with an I_n that exceeds 0.75 $I_{\max}$ (C_r $3K_m$. Concentrations beyond this threshold may cause salinity and reduced influxes of other nutrients (Bar-Yosef, 1999). Nutrient influx into plant roots usually follows a saturation curve (Jungk, 1996), as Figure 10 shows. It can be seen that as the soil solution concentration increases beyond 10-mmol m^{-3} ($\cong 3K_m$), the corresponding increase in I_n, is reduced. This reiterates the point that any concentration (C_1–$C_{I\min}$) greater than $3K_m$ is likely to contribute to salinity and cause reduced influxes of other nutrients around the roots.

The concentration of a nonreactive nutrient (N for example) in the irrigation water (C_{iw}) can be taken to be approximately the same as the concentration of the bulk soil solution (C_b), but not as the same concentration as at the root surface (C_{iw}). On the other hand, if a nutrient is reactive (P for example), then C_{iw} should be corrected for adsorption to be able to maintain the correct concentration of the nutrient in the bulk soil solution. The difference between C_r and C_b can be attributed to the slow transport of nutrients from the bulk soil solution to the root surface and the fast depletion of nutrients by the roots (Bar-Yosef, 1999). An alternative solution to nutrient uptake and concentration profiles around a radial root segment was derived by de Willigen and Van Noordwijk (1994) and subsequently implemented by Heinen (1997).

Table 5 shows the uptake of NPK as influenced by corn age growing under field conditions. It can be seen from Table 6 that the majority of N is taken up in the first 20 days, and then the N uptake drops drastically 10 days later. But P is not significantly taken up by corn when compared to N and K uptake.

Electroneutrality during ion uptake

During the process of nutrient uptake as ions by plants, electroneutrality is maintained in the soil solution and nutrient solution in the plants (Bar-Yosef, 1999; Kirkby and Knight, 1977). When excess of cations are taken up compared to anions, plant roots compensate by excreting protons (H^+). This usually leads to acidification of the rhizosphere. But if anions are taken up more than cations, plant roots will excrete hydroxyls (OH^-). Hydroxyls so released readily react with carbon dioxide to form hydrogen carbonate (HCO_3^-), leading to alkalization of the rhizosphere (Hinsinger, 1998; Kirkby and Knight, 1977; MacKnown et al., 1982). Thus, plants taking up more NO_3^- over cations will raise the soil solution pH, and those taking up excess ammonium or other cations will acidify it.

The pH level of the soil solution affects the dynamics of nutrients in the soil solution and the soil. For example, in soils with high Ca^{2+}, such as Millville silty loam soil used in our experiments, if plants take up more nitrates than cations, then Ca^{2+} can react with HCO_3^- to form insoluble calcium carbonate salts. Precipitation of calcium carbonate will lower the EC of the soil solution and possibly increase the SAR of the soil solution. Since the TDR measured EC_b considers total ionic effect of all soil solution constituents, then the measurement of NO_3^- EC dynamics in the presence of root uptake of nitrates and in Ca^{2+} rich soils is likely to be buffered with the net result of salt removal and reduction in EC_b. In other systems this may not be the case, and the dynamics of NO_3 uptake measured by TDR may be obscured by introduction of soluble ‘replacement’ salts into the soil solution. This monitoring problem could possibly be solved by use of solute specific sensors or supplemental pH information.

Monitoring nitrate dynamics – experimental evidence

Volume balance

For both the greenhouse and field experiments (see ‘Experiments on water and solute movement and distrubition’) section, a high resolution monitoring grid made of TDR probes was used for temporal and spatial monitoring θ and EC_b, as shown by Figure 11a (see also Mmolawa, 2000; Mmolawa and Or, 2000). Figure 11b is a close-up look at an elemental volume for a TDR probe (0.15 m long, three-prong design), monitoring simultaneously soil water content and soil

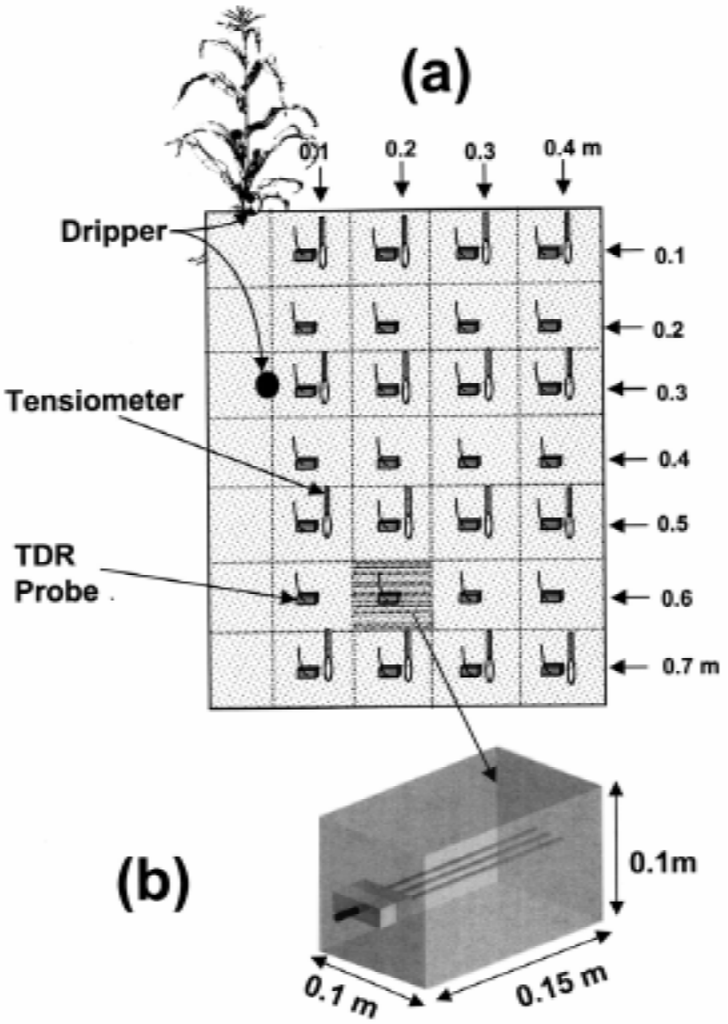

Figure 11. Control soil volume (0.1 m × 0.1 m × 0.15 m) used for analysis of the soil water dynamics as influenced by soil water concentration, soil bulk EC, presence and no presence of plant root water uptake.

bulk electrical conductivity (EC). In their soil water study, Coelho and Or (1996) assumed that soil water dynamics at a position on the plane (r, z) result only from interactions between water flow emanating from the point source (dripper) and root extraction. Other possible influences from soil evaporation and deep percolation were considered negligible. Thus, water content prediction at a given location (r, z) is due to the analytical transient flow solution (Warrick, 1974) and changes in water content due to plant uptake at the same volume element (r, z). Although this localized water volume balance excludes interactions in the entire wetted volume, the local water balance within a measurement volume is preserved.

Water uptake by the volume balance model

According to the local balance approach, the transient water content at a location (r, z) is given by (Or and Coelho, 1996):

$$\theta(r, z, t) = \theta_{\text{flow}}(r, z, t) - \Delta\theta_{\text{uptake}}(r, z, t - t_0) \quad (31)$$

θ_{flow} (r, z, t) is the water content based on Warrick's (1974) transient flow solution from point sources. The analytical solution for transient matrix flux potential distribution for a buried point source Φ_{pB} is (Warrick, 1974):

$$\Phi_{\text{pB}}(R, Z, T) = \frac{e^{z}}{2\rho}\left[e^{\rho}\text{erfc}\left(\frac{\rho}{2\sqrt{T}} + \sqrt{T}\right) + e^{-\rho}\text{erfc}\left(\frac{\rho}{2\sqrt{T}} - \sqrt{T}\right)\right] \quad (32)$$

and for a surface point source the solution is:

$$\Phi_{\mathrm{pS}}(R,Z,T) = 2\left[\Phi_{\mathrm{PB}} - \mathrm{e}^{2z}\int_{z}^{\infty}\mathrm{e}^{2z'}\right.$$
$$\left.[\Phi_{\mathrm{PB}}]_{z=z'}\mathrm{d}Z\right] \quad (33)$$

where the dimensionless variables $R = \alpha\, r/2$, $Z = \alpha z/2$, $T = \alpha kt/4$, $\rho = (R^2 + Z^2)^{0.5}$, and $\Phi = \alpha q\phi\,/8\,\pi$ are used; q is the discharge of the point source. For the sake of completeness, we mention the solution of Revol et al. (1997) for time dependent flow from surface dripper as a potential alternative formulation to Equation (33). Equation (7) is then used to transform matrix flux potential to matric head distribution. Then θ_{flow} is obtained from matric head distribution by using a retention model by Russo (1988):

$$\frac{(\theta_{\mathrm{flow}} - \theta_{\mathrm{r}})}{(\theta_{\mathrm{s}} - \theta_{\mathrm{r}})} = [\mathrm{e}^{0.5\alpha h}(1 - 0.5\alpha h)]^{\frac{2}{\mu+2}} \quad (34)$$

where θ_r and θ_s are the residual and saturation water contents respectively, and μ is a pore connectivity parameter. But $\Delta\theta_{\mathrm{uptake}}$ in Equation (31) is the cumulative root water uptake at location (r, z) since starting time t_0 after irrigation (Or and Coelho, 1996):

$$\Delta\theta_{\mathrm{uptake}}(r,z,t-t_0) = \int_{t_0}^{t} u^*(r,z)\mathrm{d}t \quad (35)$$

where $u^*(r, z)$ is the actual uptake at (r, z) given by the product of plant transpiration rate and two-dimensional uptake intensity, $u(r, z)$. This $u(r, z)$ gives the two-dimensional uptake intensity as a fraction of the total uptake intensity for a given entire wetted region. The uptake intensity at (r, z) for a buried dripper in a crop row is given by the bivariate normal distribution function (Or and Coelho, 1996):

$$u(r,z) = \frac{\beta}{2\pi S_r S_z}$$
$$\exp\left\{-0.5\left[\frac{(r-m_r^2}{S_r^2} + \frac{z-m_z)^2}{S_z^2}\right]\right\} \quad (36)$$

Equation (36) above is similar to Equation (17) using similar symbols and notation. The hourly transpiration rate was approximated using (Coelho and Or, 1996):

$$T_r(t) = \frac{T_r^*\sin^n(\omega t)}{\int^{24} 0\sin^n(\omega t)\mathrm{d}t} \quad (37)$$

where for these experimental data $n = 8$, $\omega = 2\pi/p = 0.065$ per hour, $p = 96$ hours, $T_r{}^*$ is the total daily transpiration, t is the time of transpiration during the day.

Figure 12a depicts the temporal changes in measured soil water content during the presence of plants and when plants are removed. The difference in water content in Figure 12a attributed to root water uptake is approximated by Equation (31). The uptake intensity for the monitoring TDR probe at $r = 0.10$ in and $z = 0.25$ m is calculated by optimization of Equation (35) with m_r, m_z, S_r, S_z and β as fitting parameters. Figure 13 shows the soil water dynamics for both measured and modeled water contents using Equation (33). It can be seen that the local water volume balance approach predicts the measured water content dynamics quite well.

Solute uptake by the volume balance model

In order to calculate the solute taken up by plants, we make the assumption that (a) dissolved solutes are convectively transported with the mainstream soil water flow, and (b) the solutes are nonreactive and nonadsorbing for the duration of our monitoring period.

Figure 12 will be used to demonstrate how we calculated N uptake rate. From the measured θ and EC_b, Figures 12a and b, respectively, there is more decrease in θ and EC_b when plants are present than when they are removed, especially during the daytime periods. These differences in measured θ and EC_b can only be attributed to root uptake of water and solutes, because the soil volumes at which these measurements were taken remained the same for both experiments. Using Equations (39) and (40) in the ‘Appendix’, temporal soil solution concentration and mass variation were calculated and plotted as shown in Figure 12c, d.

From Figure 12d (WP), the change in mass between $t = 40$ hours (after redistribution has taken place) and $t = 95$ hours (before the next irrigation) is 0.060 g. This gives a KNO_3 uptake rate of 0.026 g d^{-1} 1500 cm^{-3} between 86 to 89 DAE. Since the uptake intensity at this location ($r = 0.10$ m and $z = 0.25$ m) is only a fraction (0.058) of the total uptake intensity of the entire monitoring zone, then we need to upscale this uptake rate to the entire monitoring zone. Scaling up this uptake rate to the entire monitoring grid similar to Figure 11a, we have 0.45 g d^{-1}. Since NO_3 is 61% of KNO_3 then the uptake rate is 0.27 g m^{-2} d^{-1} per plant for $N)_3$–N uptake. Similarly the N uptake was calculated for other locations as shown in Table 7.

The average $N)_3$–N uptake was found to be 0.5 g m^{-2} d^{-1} per plant between 86 and 89 DAE, which compares well with the sweet corn $N)_3$–N uptake rate of 0.3 g m^{-2} d^{-1} per plant during 71–80 DAE by Bar-Yosef (1999). The N uptake by the TDR measured soil water content and EC_b was only detectable at a radius of 0.10 m around the dripper. At radial distances beyond 0.10 m, N uptake was confounded by several

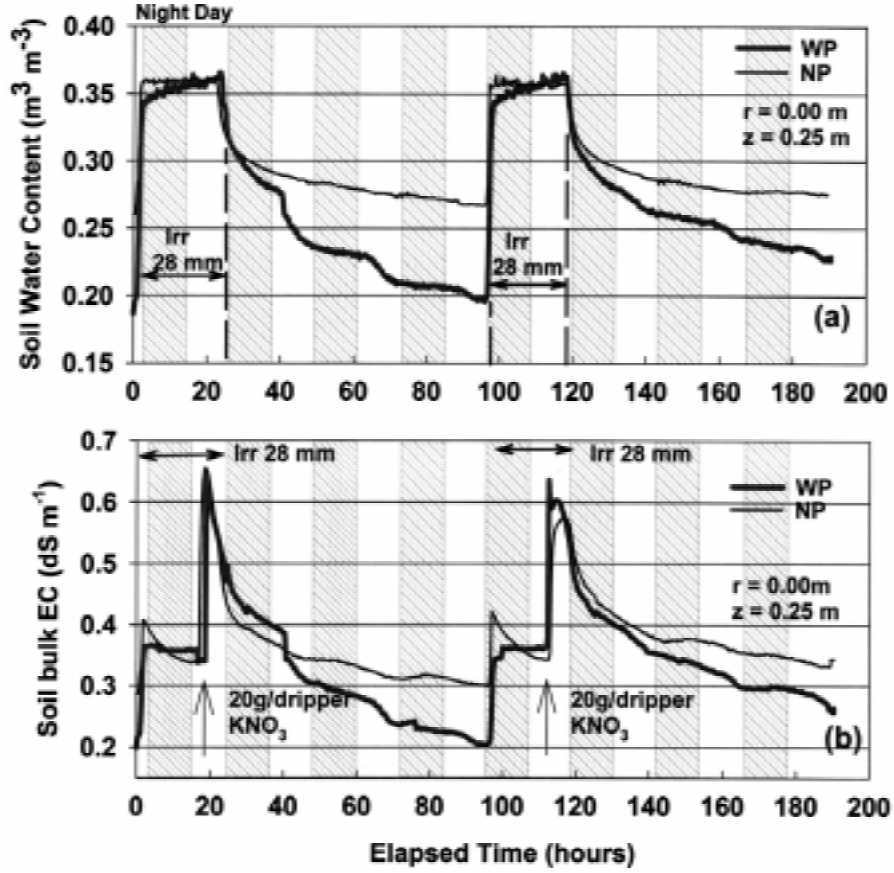

Figure 12. Temporal variations of the volumetric soil water content and EC_b, as well as soil water solution concentration and mass dynamics with time. Temporal changes for these parameters are for with-(WP) and without-plants (NP) scenarios at an observation point at r = 0.10 m and z = 0.25 m, with the buried dripper on crop row at r = 0.0 m and z 0.25 m. Dripper discharge is q = 1.6 L/h. (a) Measured temporal volumetric soil water content changes for a buried dripper beneath a crop row (b) Measured temporal dynamics of soil bulk EC, the figure also shows the diurnal EC_b fluctuations. (c) Calculated temporal soil water concentration dynamics, (d) Calculated mass changes in a given soil volume.

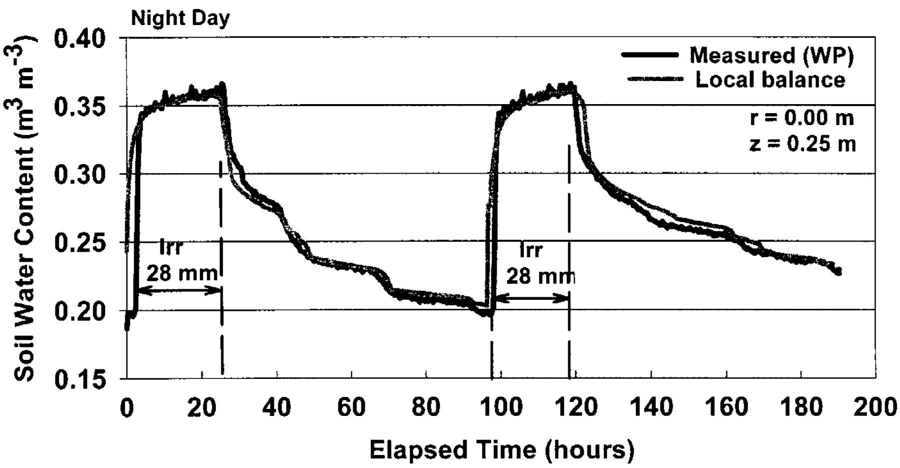

Figure 13. Measured and predicted water content for a control volume as shown by Figure 11b. The predicted water content is by way of Equation (34).

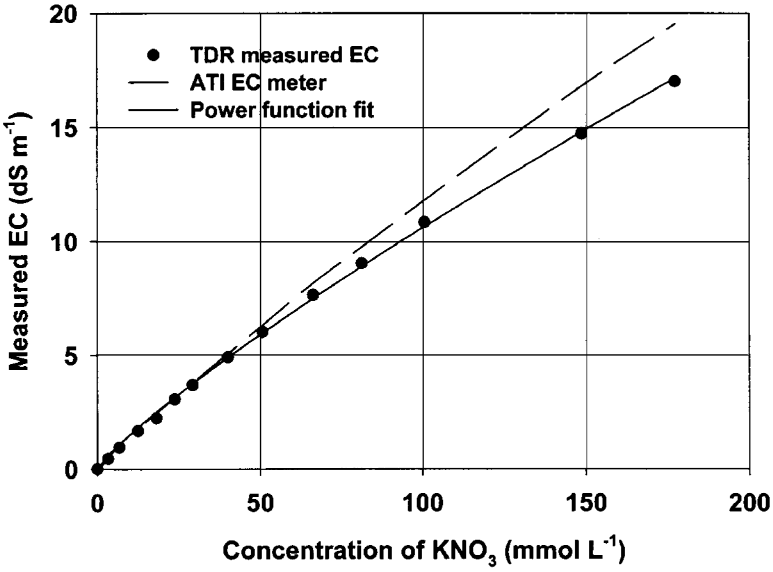

Figure 14. The relationship between measured EC and solution KNO_3 concentration established in the laboratory. The TDR measured EC readings were also measured with an ATI EC meter.

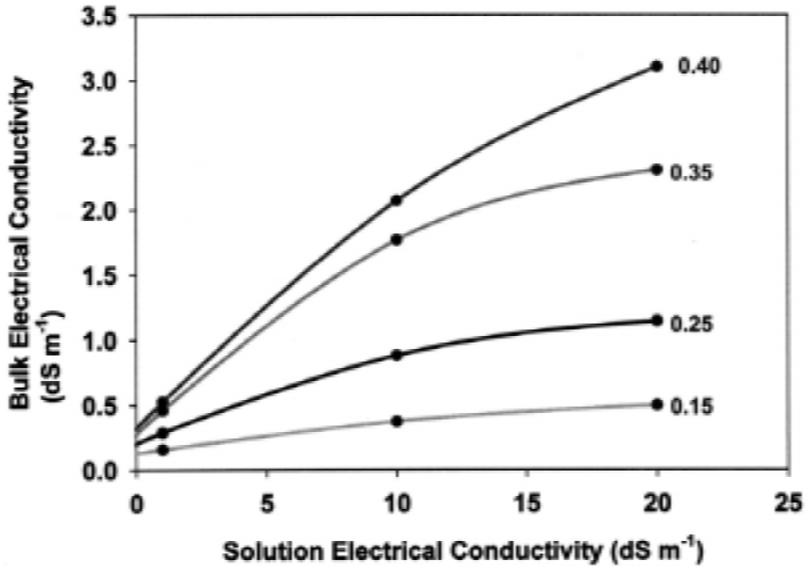

Figure 15. The EC_b and EC_{SW} relationship at fixed volumetric water contents (m^3 m^{-3} of 0.4, 0.35, 0.25 and 0.15. Extrapolation of these four curves to EC_{SW} = 0 gives an approximation to EC_S.

processes taking place in the rooting zone, such as exchange of ions at the root surfaces during plant uptake of solutes to maintain elctroneutrality both inside the plant and the rhizosphere.

Summary and conclusions

The uptake of water and solutes and, therefore, the resulting distribution and dynamics of water and solutes, largely depends on the root distribution and activity of the plants, as well as the solute or nutrient being introduced into the soil rooting zone. Upon extraction of water and nutrients from their immediate vicinity, roots create gradients in the soil water potential and in the nutrient concentration of the ambient solution. As a result, water and solutes will move along these gradients by mass flow and diffusion. In most cases, models developed to capture soil water and solute dynamics patterns are usually a function of root distribution or some root properties, like root elong-

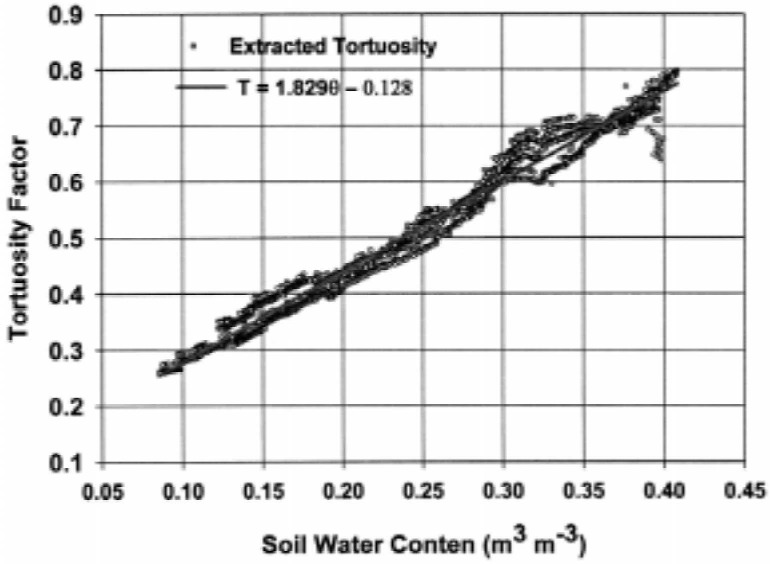

Figure 16. Both the extracted tortuosity from measured EC_b and fitted linear model tortuosity factor as functions of water content for Millville silt loam soil.

ation rate, root length or density. But in practice, it is quite a formidable task to measure and distinguish between temporal changes in bulk soil solution concentrations and rhizospheric solution concentration. Consequently, transient root water and solute uptake is still a challenge.

Usually the main goal for modeling root distribution is to be able to relate it to the plant water uptake patterns. Even though root distributions in most cases can shed some light on the way the water and solute uptake patterns are going to be distributed, other factors affect the root water and solute uptake. Concise information regarding root distribution and root water uptake patterns is essential for a good understanding of soil water and solute dynamics in the vadose area, sound fertigation management, and irrigation systems design.

Other inputs to the solute dynamics in the rooting zones are the irrigation method and the quality of the irrigation water. Irrigation and or fertigation with water of doubtful quality can exacerbate existing salinity problems if leaching and other management practices to avoid salinity are not strictly enforced. Drip irrigation, because of its frequent and small applications of water, is capable of minimizing the amounts of salts applied per irrigation, thereby reducing the salinity hazard.

Our approach was to measure simultaneously water content and EC_b, both on temporal and spatial variation using TDR. The outstanding advantage of this approach is that we were able to monitor simultaneously both the water content and soil solution solute mass changes spatially and temporally. The problem with this approach is that TDR measures EC due to total ionic behavior and is not ion specific in measuring the soil solution EC. Since we calculated the soil solution concentration from the measured EC_b, it is possible that other ions from the soil contributed or influenced the measured EC_b.

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Appendix

Relationship between soil solution concentration, bulk EC, and mass of dissolved salts in a given control soil volume

To be able to keep track of solute movement in the soil, we need to know the soil water concentration changes temporally and spatially at targeted locations in the soil profile. Acquiring temporal and spatial changes in soil water solution concentration changes will enable mass balance calculations that are fundamental in any attempt to model solute movement.

But field measurement of the soil water concentration usually requires use of solution samplers that are both destructive to the soil and are expensive (Risler et al., 1996). In this study, the approach is to establish a relationship between the soil water solution concentration and the soil water solution electrical conductivity (EC_{SW}). Then the EC_{SW} can be related to the soil bulk electrical conductivity (EC_b), which can be easily measured by way of the time domain reflectometry (TDR). According to the work done by Rhoades et al. (1976), the equation relating EC_b and EC_{SW} requires knowledge of the tortuosity factor of the soil. Hence, laboratory experiments were conducted to evaluate the tortuosity factor for Millville soil used in field experiments in this study.

According to Rhoades et al. (1976), EC_b is related to the soil water content and EC_{SW} empirically as:

$$EC_b = \tau\theta EC_{SW} + EC_S \qquad (38)$$

where EC_b is the soil bulk EC, θ is the volumetric water content, EC_{SW} is the soil water EC, τ is the Tortuosity factor (or transmission coefficient related to the pore geometry), EC_S is the surface conductance of the soil. The tortuosity factor has been found to be a linear function of water content as (Rhoades et al., 1976):

$$\tau = a\partial + b \qquad (39)$$

where a and b are constants that vary for different soils.

Since EC_S does not depend on the water content nor the electrical conductivity of the soil solution (Rhoades et al., 1976), its average value can be used to extract the tortuosity as a function of EC_b, EC_{SW} and ∂ as follows:

$$\tau = \frac{EC_b - EC_S}{\partial EC_{SW}} \qquad (40)$$

Calibration of the TDR probe for nitrate solution

The EC of known nitrate concentrations and volumes were measured using the TDR probes. An ATI electrical conductivity meter was used to calibrate the TDR EC readings. Figure 14 shows the EC readings for both the TDR probe and the ATI EC meter for KN03 solution. Potassium nitrate was used for subsequent calibrations because that is the form of the nitrate used for field studies.

TDR EC and soil water concentration relationship

Small plastic containers were all filled with equal amounts of sieved and dry Millville silt loam soil. The soil was sieved with a 2 mm sieve. The soil in containers 1, 2 and 3 were saturated with 1500 cm^3 of 20 dS m^{-1} KNO_3 solution, soils in containers 4, 5 and 6 were saturated with 10 dS m^{-1} solution of KNO_3 solution, and containers 7, 8 and 9 saturated with distilled water and the background EC_{SW} in these containers was approximately 1 dS m^{-1}. The electrical conductivity of the soil water solution in all the containers was equal to the EC of the saturating liquid at the saturation point of the soil. But as the pans were left to evaporate and dry, the EC_{SW} changed with the water content status. TDR probes were used to measure simultaneously the volumetric water content and the bulk EC of the soil water solution as the soil dried. From this experiment, the concentration of the soil water solution was calculated as a function of water content. As for the drying soil column experiments, the water content and the EC_b were measured continuously by the TDR from the soil saturation to very dry soil conditions. Since we are interested in the soil water concentration relationships with the EC_b, the soil water concentration was calculated as follows:

$$C = \frac{M}{V_{SW}} \tag{41}$$

where C is the soil water concentration (g cm^3). M is the mass of KNO_3 in the soil water (g); it is the product of the concentration and volume of potassium nitrate solution added to the soil. V_{SW} is the soil water volume which is a product of soil volume and volume of soil water (cm^3). Then the relationship between the TDR EC_b and soil water concentration was established.

Approximation of the soil surface conductance, EC_S

Electrical conductivity of the soil solution was plotted with soil bulk EC at fixed water contents of 0.4, 0.35, 0.25 and 0.15, in all the pans used in part 2 above. The EC_S was estimated by extrapolating the graphs in Figure 15 to $EC_{SW} = 0$.

The resulting extracted and optimized tortuosities by Equations (39) and (38), respectively, were plotted against water content as shown by Figure 16. The soil water concentration and soil water electrical conductivity are related by Equation (42) below:

$$EC_{SW} = 0.215 \cdot C^{0.845} \; or$$
$$C = \left[\frac{EC_{SW}}{0.215}\right]^{\frac{1}{0.845}} \tag{42}$$

where C is the concentration in meq L^{-1} or mmol L^{-1}.

The surface conductance of the Millville silt loam soil is 0.1276 dS m^{-1}.

The tortuosity factor for the Millville silt loam soil is $\tau = 1.829\partial - 0.128$.