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REVIEW

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The resource potential of in-situ shallow ground water use in irrigated agriculture: a review

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Abstract Shallow ground water is a resource that is routinely overlooked when water management alternatives are being considered in irrigated agriculture. Even though it has the potential to provide significant quantities of water for crop use under the proper conditions and management. Crop water use from shallow groundwater is affected by soil water flux, crop rooting characteristics, crop salt tolerance, presence of a drainage system, and irrigation system type and management. This paper reviews these factors in detail and presents data quantifying crop use from shallow ground, and describes the existing state of the art with regard to crop management in the presence of shallow ground water. The existing data are used to determine whether in-situ crop water use from shallow ground water is suitable for a given situation. The suggested methodology uses ratios of ground water electrical conductivity to the Maas–Hoffman yield loss threshold values, the day to plant maturity relative to plant growth period, and the maximum rooting depth relative to the nearly saturated zone. The review demonstrates that for in-situ use to be feasible there has to be good quality ground water relative to crop salt tolerance available for an extended period of time. Shallow ground water availability is one area that can be managed to some extent. Crop selection will be the primary determinant in the other ratios.

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Introduction

Competition for water between urban, industrial, environmental, and agricultural interests will intensify in the future. Recent studies project that the world population will increase to 9 billion people by 2050 from a current population of approximately 6 billion (U.N. 2004). This population increase will bring additional demands for food, clean water for drinking, water for the environment, and production of consumer goods from the existing water supply. Irrigation supplies approximately 40% of the world foodstuffs on less that 18% of the arable land and has a significant future role in meeting the projected world food demand (Postel 1999). Approximately 80% of the developed water supply worldwide is used for irrigation and this water is a logical source for meeting the other water demands.

A complementary approach to new irrigation water development will be to increase water use efficiency through improved irrigation technology, improved crops, and improved productivity of lands adversely impacted by high water tables and salinity. Currently, surface irrigation is the principal irrigation method used throughout the world and the resulting average world irrigation efficiency is in the range of 30–50%. This poor efficiency provides opportunities for improvement that should result in additional water supply for other uses without negatively impacting production, since low irrigation efficiency is often responsible for extensive areas of water logging and shallow ground water. Improved irrigation management will reduce water logging and the volume of deep percolation and should result in improved yields. However, there is still a need for limited amounts of deep percolation to manage salinity in the root zone, potentially resulting in areas of shallow ground water that need to be controlled.

Shallow ground water is a resource that is available to meet crop water demands either through in-situ use or by using drainage water for supplemental irrigation (Ayars and Schoneman 1986; Ayars et al. 1986, 1993, 1998; Ayars 1996, 1999). Depending on the crop and shallow ground water quality, each of these techniques is used with varying degrees of success and there are management challenges associated with each method.

Saline drainage/ground water has been studied extensively as a supplemental source of irrigation water (Ayars et al. 1993; Rhoades et al. 1980, 1989; Rhoades 1989; Rhoades 1984). Rhoades et al. (1989) found the cyclic use of low to moderately saline water and good quality water to be an effective method for using saline water as a supplemental irrigation supply without having negative effects on yield and soil quality. Ayars et al. (1993) used saline (7 dS/m) water to irrigate cotton and found that yields were maintained and that soil salinity could be managed with a pre-plant irrigation of good quality water. The high level of boron in the drainage water and the accumulation of boron in the crop root zone in the study by Ayars et al. (1993) was identified as a potential problem in long term use of water containing high levels of boron.

Major benefits of applying drainage water with an irrigation system are that it can be used for a longer time period during the growing season and the determination of the depth of application is relatively straightforward. Any irrigation scheduling method can be used to determine the depth and timing of the application and a leaching fraction can be added to the applied water based on the water quality, the irrigation system in use, and the crop salt tolerance.

In-situ use by crops is a more complicated system than surface application because there is limited information on potential crop water use from shallow ground water and how to achieve the maximum use potential. Even though there has been extensive research describing in-situ crop water use from shallow ground water by a wide variety of crops over the past 50 years, the full potential of this resource has not been quantified.

Crop water use from shallow ground water is affected by depth to ground water, ground water quality, crop growth stage, crop salt tolerance, irrigation frequency and application depth, and whether it is an annual or perennial crop. This level of complexity makes it impossible to conduct experiments that cover all the factors at once and the research would be focused on only a single component, i.e. water use relative to the water table depth, or ground water quality, or soil type.

As a result, much of the literature quantifies the amount of water use for the existing conditions of the experiment but provide little information on how to extend this information to other situations.

The primary methods for estimating crop water use from shallow ground water have been by direct measurement with weighing and drainage lysimeters or calculation of a residual term using a mass balance equation. Each of these methods has problems and errors. The cost of construction, operation, and maintenance of a weighing lysimeter is a major limitation of this technique. As a result, much of the lysimeter research is done using small soil columns that can be operated as either drainage or weighing lysimeters.

Use of a mass balance equation requires computing crop use from ground water as a residual based on the measurement of evapotranspiration, deep percolation, surface runoff, applied water, and change in stored soil water. Each of these components is subject to measurement errors that affect the final result. The major source of error is probably evapotranspiration since usually workers do not take direct measurements of this component and it is usually calculated based on climate measurements.

The objective of this review is to summarize previous research findings related to in-situ crop water use from shallow ground water and to provide a decision framework for irrigation water management to maximize crop water use from shallow ground water.

Factors affecting crop water use from shallow ground water

Soil water flux

Studies of crop water use from shallow ground water generally report the water depth below the soil surface, but the important statistic is the distance between the ground water surface or the nearly saturated zone and the bottom of the root zone. This is the distance water must flow to become available to the crop. The flux to the root zone will be determined by the unsaturated soil hydraulic conductivity, which is determined by the soil type, and the soil matric potential gradient established in the soil profile as a result of both crop water use and evaporation from the soil surface. Soil water flux is often computed in one dimension using Darcy's law as shown in Eq. 1

$$z = \int_0^{hz} \frac{\mathrm{d}h}{1 + q/k(h)}, \tag{1}$$

where z is the distance between the water table and a position in the soil profile with a constant flux of q. The hydraulic conductivity (k) is given as function of the matric potential (h). Since the unsaturated hydraulic conductivity is a function of the soil type, it is apparent that the soil type is a dominant factor affecting the flux from the water table to a plant. The closer the root zone is to the water table the higher will be the potential crop water use since it is possible to maintain the flux at a higher rate over a shorter distance. There is still the problem of creating the gradient needed to move water up in the profile. It has been demonstrated that plants will take water from the areas of the soil profile with the highest potential energy, so the higher the soil water content in the root zone the lower is the potential for use from shallow ground water. This means that the soil in the root zone has to be dried out sufficiently to create an upward gradient. The gradient is also affected by the osmotic potential in the soil water and ground water.

Wu et al. (1999) modeled crop water use from shallow ground water with an empirical model developed by W.S. Meyer that tries to capture the interaction of soil water content, root development, crop water requirement, and soil type. The equation is

$$q_{\mathrm{u}} = \frac{a}{\mathrm{e}^{b(Z_R/Z_{\max})}\left(1 + \mathrm{e}^{C/(x+0.01)}\right)} \times ET, \tag{2}$$

where q_{u} is upflux (mm/day), a,b,c are regression coefficients, Z_R is the depth from 1/3rd of the depth of the root zone to the ground water level (m), $Z_{\max}$ is the threshold water table depth below which upflow would be less than 1 mm/day as defined by Talsma (1963) (m), and x is the relative water content described by the relation

$$x = \frac{\theta_{\mathrm{s}} - \theta_{\mathrm{avg}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{l}}}, \tag{3}$$

where θ_{s} is saturated water content, θ_{l} is lower limit of plant available water, and θ_{avg} is average water content of the unsaturated layer. The values suggested by Wu et al. (1999) for the regression coefficients are $a=3.9$, $b=3.8$, and $c=0.5$. The suggested values for $Z_{\max}$ are soil dependent and vary from 1.5 m for coarse sand, 6 m for sandy clay loam, and 1.5 m as the clay content increases above the sandy clay loam. The $Z_{\max}$ indicates the upflux potential for the soil type and should be related to hydraulic conductivity, air entry value, and soil water retention curve for a certain soil. Wu et al. (1999) provided a graph of the proposed values for $Z_{\max}$. It can be seen that the first part of the Meyer equation 2 is the percentage of shallow ground water that is used to meet crop ET.

Several formulas have been derived for estimating flow from a water table to fallow and crop land. Darcy's law (Eq. 1) was simplified and solved analytically by using an exponential form for the hydraulic conductivity function for the soil being studied. The maximum steady state flux then becomes

$$q_m = A\mathrm{e}^{-bz}, \tag{4}$$

where q_m is the flux, and A and B are regression coefficients related to the soil properties, and z is the depth to the water table (Ragab and Amer 1986). Use of this expression gives an indication of the potential crop water use for the given conditions.

Another equation used to quantify upflux is

$$q_{\mathrm{u}} = aD^b, \tag{5}$$

where q_{u} is the upward flux from the water table at depth "D" and "a" and "b" are empirical constants that depend on the soil hydraulic parameters. The values for "a" appear to be specific to the soil of interest where "b" appears to represent a soil type. (Grismer and Gates 1988).

Other research (Grismer and Gates 1988) has indicated that upflux from the water table may be adequately represented by

$$q_{\mathrm{u}} = a - bD. \tag{6}$$

As in Eq. 5 the values for "a" are highly variable while the values for "b" depend only on the soil type. Grismer and Gates (1988) demonstrated the application of this equation for cotton water use from shallow ground water on three different soil types. The regression equations for water use by cotton from shallow ground water in different soils are shown in Fig. 1. The data demonstrate that for a given depth to the water table the percentage of water extracted from the water table is reduced as the soil clay content increases. This is a consequence of a reduction of the unsaturated hydraulic conductivity in finer textured soil. The data also show that for a given soil type, an increase in the depth to the water table results in a reduction of crop water use from the shallow ground water, as predicted in Eq. 1.

Much of the research on crop water use from shallow ground water has been done in lysimeters with a fixed depth to water (Shih and Snyder 1984; Meyer et al. 1990a, b; Kruse et al. 1993; Hutmacher et al. 1996; Schneider et al. 1996; Zhang et al. 1999; Kang et al. 2001). These workers used water table depths in the range of 0.3–2.1 m and maintained the water table at the specified depth for the duration of the experiment. The lysimeters were constructed using both disturbed and undisturbed soil cores and in the field. In field situations where the water table depth cannot be controlled, the depth to water was characterized as an average depth (Benz et al. 1987).

Roots

The root system is the least quantified aspect of the system and it is one of the most important components since it is the conduit between the vegetative portion of the plant and the soil water. Neither root development in relation to the crop growth stage nor maximum rooting depth is reported in studies on crop water use from shallow ground water. Model development and the potential for better understanding of crop water use from shallow ground water are limited without data describing the root system and its interaction with the ground water.

Crop water use from ground water will not be significant until the root zone develops into the proximity of the water table and there is an adequate gradient to induce flow to the root system. It is obvious that the quicker the root system develops to its maximum depth, the longer will be the opportunity for crop use and the larger will be the contribution from the ground water. The soil type will determine the required position of the root zone relative to the water table to allow significant

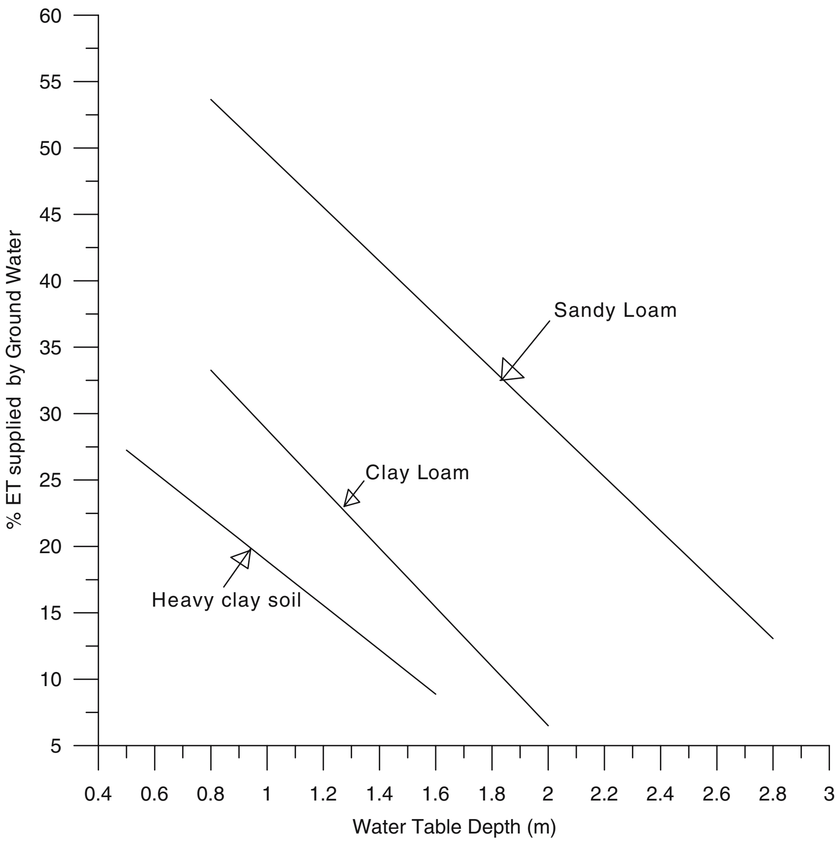


Fig. 1 Evapotranspiration from shallow ground water by cotton as affected by soil and water table depth. (After Grismer and Gates 1988)

crop use. The air entry pressure determines the point at which soil is nearly saturated and capable of supplying water at rates that are nearly equal to the saturated hydraulic conductivity. For coarse soil with low air entry pressure, the roots will have to be close to the water table while in loam soils and soils containing larger percentages of clay with higher air entry pressures, the roots will not have to be as near to the water table to still be effective in using ground water.

Borg and Grimes (1986) developed an equation describing root development as a function of total growth period, days to maximum rooting depth, and days after planting. The equation is

$$\mathrm{RD} = \mathrm{RM}_m[0.5 + 0.5 \times \sin(3.0. \times (\mathrm{DAP}/\mathrm{DTM}) - 1.47)], \tag{7}$$

where RD is root depth, $\mathrm{RM_m}$ is maximum root depth, DAP is days after planting, and DTM is the days to maximum rooting depth. They provided representative data for maximum rooting depth and these data in combination with the soil data and the depth to water table provide a basis for the characterization of potential crop water use from shallow ground water (Borg and Grimes 1986).

There is also the question of the portion of the root zone that is most effective in water extraction. Research has shown the presence of roots at given depth prior to the time that significant water reduction occurs in the soil profile at that depth (Robertson et al. 1993). The Meyer equation suggests that the most significant part of the root zone is the top 1/3 which is generally the area of maximum root density. Other research, (Reicosky et al. 1971) demonstrated that the majority of the water being used by soybean grown in the presence of shallow ground water was extracted by the small portion of the root zone next to the capillary fringe. This supports the idea that the maximum potential will be met when the roots are close to the water table. Soppe and Ayars (2002) demonstrated with a safflower crop that nearly 40% of crop water use was obtained from the bottom of the root zone during periods of maximum demand.

Crops

Any plant may extract water from shallow ground water, the focus of this paper is on agronomic plants that are used in food and fiber production. Plant characteristics that affect the potential contribution of ground water to the crop water requirement include salt tolerance, length of growing season, and rooting characteristics.

Plant salt tolerance is a dominant factor affecting crop water use. Maas and Hoffman (1977) characterized plant salt tolerance based on the loss of yield as a function of increased salinity in the root zone. Their equation describes the salt tolerance using a threshold value at which yield loss begins and a coefficient that describes the rate of yield loss with increased soil salinity beyond the threshold salinity value (Maas and Hoffman 1977). This yield salinity function provides a basis for considering the potential crop water use from shallow ground water. In general, if the electrical conductivity (EC) of the ground water is less than the Maas–Hoffman threshold EC for the crop, the potential water use should be limited by factors other than salinity. Reduced uptake by plants would be theorized when the ground water EC exceeds the Maas–Hoffman threshold. However, Ayars and Hutmacher (1994) found that cotton used the same amount of water from a saline water table with an EC equal to twice the threshold as from a low salinity control. This is probably the result of several factors. The plant has had time to develop and is in a more salt tolerant stage when the maximum contribution is occurring. Also, plants respond to average salinity in the root profile and the root zone average is below the threshold. There has been a dilution of the ground water by deep percolation.

The salinity tolerance is not a static value. It has been observed that plants tend to be more salt tolerant in later growth stages than at germination (Maas 1990). This means that while the threshold value is a starting consideration, it is not the only consideration when selecting crops for use in shallow ground water areas and in managing irrigation to induce water use from the water table.

A wide range of crops have been successfully grown in the presence of shallow ground water and used ground water to provide a significant portion of the crop water requirement. The salt tolerance of these crops ranges from sensitive (lettuce) to tolerant (cotton). The majority of the crops used in shallow ground water areas are moderately salt tolerant or salt tolerant based on the Maas–Hoffman (1977) criteria and are deep-rooted crops. Table 1 lists crops that have successfully used shallow ground water. There are other crops that have been studied for yield and physiological responses in the presence of ground water but data has not been presented to describe crop water use from shallow ground water.

The total amount of water used by the crops in Table 1 varies widely depending on the salinity of the ground water in relation to the crop tolerance, the irrigation management, the irrigation water quality, the soil type, and the depth to ground water. Many of the studies and the study parameters are summarized in Table 2. In many instances, the percentage contribution exceeded 50% of the total water requirement (Kruse et al. 1993; Wallender et al. 1979; Chaudry et al. 1974). This was generally accomplished with a low irrigation frequency, once or twice a week, to every 3 weeks with a deep-rooted crop, and a good correspondence between ground water quality and crop salt tolerance (Wallender et al. 1979). Hutmacher et al. (1996) demonstrated that crops will use significant quantities of water from saline water with an EC of three to four times the Maas Hoffman (1977) threshold. However, the percentage contribution from the ground water decreases rapidly as the salinity increases and irrigation is required to meet the crop water requirement to sustain yield.

The combined matric and osmotic potential in the soil water in the crop root zone may affect the ground water contribution. As the potential energy in the soil water decreases in the portions of the crop root zone due to either increased salinity or decreased water content, there is a shift to extract more water from the ground water because the matric potential increases close to the

Table 1 Crops reported to have successfully used water from shallow ground water and references

Crop	Reference
alfalfa	Benz et al. (1983, 1987), Grimes and Henderson (1984), Kruse et al. (1993), Meyer et al. (1996), Meyer (1996), Smith et al. (1996); Zhang et al. (1999)
Bell pepper	Dalla Costa and Gianquinto (2002)
Carrot	Schmidhalter et al. (1994)
Corn (maize)	Follett et al. (1974), Benz et al. (1984), Kruse et al. (1985, 1993), Kang et al. (2001), Sepaskhah et al. (2003), Ragab and Amer (1986)
cotton	Namken et al. (1969), Williamson and Carreker (1970), Williamson and Kriz (1970), Wallender et al. (1979), Grimes and Henderson (1984), Ayars and Schoneman (1986), Ayars and Hutmacher (1994), Cohen et al. (1995), Hutmacher et al. (1996)
Eucalyptus	Thorburn et al. (1995))
Lettuce	Shih and Rahi (1984)
Millet	Stuff and Dale (1978)
Pasture	Shih and Snyder (1984)
Peach	Boland et al. (1996)
Safflower	Soppe and Ayars (2002)
Sorghum	Mason et al. (1983); Shih (1984); Robertson et al. (1993); Sepaskhah et al. (2003)
Soybean	Dugas et al. (1990); Meyer et al. 1990); Meyer (1996)
String bean	Williamson and Carreker (1970); Williamson and Kriz (1970)
Sugar beet	Follett et al. (1974), Benz et al. (1984, 1987)
Sugar cane	Escolar et al. (1971), Omary and Izuno (1995), Sweeney et al. (2001)
Sunflower	Mason et al. (1983)
Tomato	Ayars et al. (2001)
Wheat	Chaudary et al. (1974), Meyer et al. (1987), Kruse et al. (1993), Kang et al. (2001)

Table 2 Summary of selected water table studies describing crop water use from shallow ground water

Crop	Threshold (dS/m)	Climate	Water management		Water table		WT quality (dS/m)	Soil type	%GW	Ref.
			Rain (mm)	Irrig. Freq	Change	Depth (m)				
Corn	1.7	Semi-arid	< 250	2–3/week	Constant	0.6	0–6	Fine sandy loam	0–58	Kruse et al. (1993)
Corn	1.7	Semi-arid	< 250	2–3/week	Constant	1.05	0–6	Fine sandy loam	0–29	Kruse et al. (1993)
Cotton	7	Semi-arid	< 150	3–5 over 4 months	Variable	1.1–1.5	6	Clay loam	0–38	Ayars and Schoneman (1986)
Cotton	7	Semi-arid	180–380	Intermittent	Constant	0.9	0.9–6	Fine sandy loam	57	Namken et al. (1969)
Cotton	7	Semi-arid	180–380	Intermittent	Constant	1.8	0.9–6	Fine sandy loam	38	Namken et al. (1969)
Cotton	7	Semi-arid	180–380	Intermittent	Constant	2.7	0.9–6	Fine sandy loam	28	Namken et al. (1969)
Sugar beet	7	Semi-arid	ND	Weekly	Variable	1.0–1.7	0.5	Sandy loam	ND	Reichman et al. (1977)
String bean	1	Humid	NA	Weekly	Constant	0.15–0.7	NS	Sandy loam	ND	Williamson (1968)
Corn	1.7	Semi-humid	< 250	Weekly	Constant	0.5,1,1.6,2	NS	Sandy loam	ND	Doering et al. (1976)
Tomato	2.5	Semi-arid	0	2–3/week	Constant	1.1	0.6–10	Clay loam	9–34	Hutmacher and Ayars(1991)
Alfalfa	2	Semi-humid	< 250	Weekly	Constant	0.4,1,1.5,2	NS	Sandy loam		Benz et al. (1987)
Sugar beet	7	Semi-humid	< 250	Weekly	Constant	1.55	NS	Sandy loam	63	Benz et al. (1984)
Lettuce	1.3	Humid	NA	Variable	Constant	0.4,0.6,0.85	NS	Muck	ND	Shih and Rahi (1984)
Alfalfa	2	Semi-humid	< 250	Weekly	Constant	0.4,1,1.6,2.1	NS	Sandy loam	28–57	Benz et al. (1984)
Cotton	7	Semi-arid	ND	ND	Variable	ND	ND	Loam to clay loam	10–53	Grismer and Gates (1988)
Alfalfa	2	Semi-arid	100	As needed	Constant	0.1	16	Loam to clay loam	19	Zhang et al. (1999)
Cotton	7	Semi-arid	100	As needed	Variable	1.7–2.1	6	Loam to clay loam	59–70	Wallender et al. (1979)
Millet	Na	Humid	ND	ND	Constant	0.76	NA	Sandy loam	NA	Williamson et al. (1969)
Corn	1.7	Semi-humid	< 250	As needed	Variable	1.5–2	ns3	Sandy loam	NA	Reichman et al. 1986
Cotton	7	Arid	< 250	2–3/week	Constant	1.2	0.3–30	Clay loam	0–42	Hutmacher et al. (1996)
Corn	1.7	Humid	< 50	No irrigation	Constant	1.05	NS	Silt loam	0–27	Stuff and Dale (1978)
Wheat	2	Semi-arid	ND	Maintain 0.3 bar	Constant	0.6	0.5, 2.9,5.2	Silt loam	70	Chaudry et al. (1974)
Wheat	2	Semi-arid	ND	Maintain 0.3 bar	Constant	0.9	0.5, 2.9,5.2	Silt loam	53	Chaudry et al. (1974)
Wheat	2	Semi-arid	ND	Maintain 0.3 bar	Constant	1.2	0.5, 2.9,5.2	Silt loam	27	Chaudry et al. (1974)
Wheat	2	Semi-arid	ND	Maintain 0.3 bar	Constant	1.5	0.5, 2.9,5.2	Silt loam	20	Chaudry et al. (1974)
Sweet sorghum	Na	Humid	ND	Maintain water level	Constant	0.3, 0.6, 0.9	NS	Muck	ND	Shih 1984)
Corn	1.7	Semi-humid	< 250	Weekly	Declining	0.6–1.5	0.6	Fine sandy loam		Follet et al. (1974)
Wheat	2	Semi-arid	Yes	Weekly	Constant	0.6–1.0	6	Fine sandy loam	23–93	Kruse et al. (1993)
Sorghum	Na	Semi-arid	Yes	Well watered	Variable	1–1.5		Clay loam to clay	42	Mason et al. (1983)
Corn	1.7	Semi-arid	Yes	Well watered	Variable	1–1.6		Clay loam to clay	40	Mason et al. (1983)
Sunflower		Semi-arid	Yes	Well watered	Variable	1–1.7		Clay loam to clay	32	Mason et al. (1983)
Cotton	7	Semi-arid		3 and 14 day		1–1.5	28–35	Clay loam to clay		Cohen et al. (1995)
Sugar cane		Humid	Yes			1,1.5,2,2.5,3,4	NS	Silty clay loam		Escolar et al. (1971)
Carrot		Humid	Yes							Schmidhalter et al. (1994)
Eucalyptus		Semi-arid	Yes	NA	Variable			Clay		Thorburn et al. (1995)
Corn	1.7	Semi-arid	Yes	Deficit 50 mm	Constant	0.6–1.3	11	Clay loam	16–29	Prathapar and Meyer (1992)
Sugar cane		Humid	No			0.5–1			65	Omary and Izuno (1995)
Corn	1.7	Semi-arid		As needed	Variable	0.4	NS	Clay loam	42	Ragab and Amer (1986)
Wheat	2									Kang et al. (2001)
Maize	1.7									Kang et al. (2001)
Winter wheat	2	Semi-arid	Yes	Soil water depletion	Constant	0.5,0.8,1, 1.2,1.5,2,2.5		Loam		Zhang et al. (1999)
Peaches		Semi-arid	Yes	Regulated Deficit Irrig.		1.4	0.1, 2	Silty clay loam	28,11,15,7	Boland and Jerie (1996)
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	1	0.1	Loam	54	Smith et al. (1996)

Table 2 (Contd.)

Crop	Threshold (dS/m)	Climate	Water management		Water table		WT quality (dS/m)	Soil type	%GW	Ref.
			Rain (mm)	Irrig. Freq	Change	Depth (m)				
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	1	0.1	Loam	48	Smith et al. (1996)
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	1	16	Loam	24	Smith et al. (1996)
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	1	0.1	Clay loam	22	Smith et al. (1996)
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	1	0.1	Clay loam	43	Smith et al. (1996)
Alfalfa	2	Semi-arid	Yes	80 mm threshold	Constant	0.6–1.3	16	Clay loam	13	Smith et al. (1996)
Wheat	2	Semi-arid	Yes		Constant	0.6–1.3	0.2	Loam	36	Meyer et al. (1987)
Soybean		Semi-arid	Yes		Constant	0.6–1.3	0.2	Loam	25	Meyer et al. (1990)
Maize	1.7	Semi-arid	Yes		Constant	0.6–1.3	0.2	Loam	39	
Lucerne	2	Semi-arid	Yes		Constant	0.6–1.3	0.2	Loam	35	Meyer et al. (1996)
Pasture	2	Semi-arid	Yes		Constant	0.6–1.3	0.2	Loam	14	
Wheat	1.7	Semi-arid	Yes		Constant	0.6–1.3	0.2	Clay loam	10	Meyer et al. (1987)
Soybean		Semi-arid	Yes		Constant	0.6–1.3	0.2	Clay loam	8	Meyer et al. (1990)
Maize	1.7	Semi-arid	Yes		Constant	0.6–1.3	0.2	Clay loam	16	
Lucerne	2	Semi-arid	Yes		Constant	0.6–1.3	0.2	Clay loam	13	Meyer et al. (1996)
Pasture	2	Semi-arid	Yes		Constant	0.6–1.3	0.2	Clay loam	9	
Maize	1.7	Semi-arid	No	4, 5, 6,	Constant	0.68	NS	Clay loam	46, 43, 39	Sepaskhah (2003)
Safflower	2	Semi-arid	No	2/week	Constant	0.8	14	Silty clay loam	25	Soppe and Ayars (2002)

ND No data, *NA* not applicable, *NS* non saline

water table even though the ground water salinity is higher than the plant would normally use. This is possible because the combined matric and osmotic potential is greater than in other portions of the root zone and the plant can use the water.

The crop growing season will impact the total crop water use in several ways. A perennial crop will have a well developed root zone in the second and subsequent years of production and thus the root zone will be well positioned to use water during the entire growing season. Annual crops grow a root system each year and have limited time available to use shallow ground water. Total use is determined by the time it takes to develop a large demand and to have the root zone close enough to the ground water to get significant transport to the root zone. The longer the growing season, the longer is the potential use from shallow ground water.

If the crop has short growing period (90 days) there is limited opportunity for crop use compared to a crop with a growing period of 200 days. Particularly when the last period in the growth cycle will be the time that the maximum demand will occur. Cotton in the San Joaquin Valley of California is grown in areas with high water tables and research has demonstrated that up to 60% of the crop water requirement can be met from a saline (7 dS/m) water table at a depth between 1 and 2 m (Wallender et al. 1979). This crop is planted in March and harvested in October with the last irrigation occurring oftentimes in August. There may be from 3 to 5 irrigations during this time. The majority of the crop water use from ground water occurs between the last irrigation and the end of the season. At this time the crop is reasonably salt tolerant, the root zone is at maximum development, in close proximity to the water table, and it is a period of maximum demand. This combination results in the maximum potential for crop water use from the shallow ground water.

Presence of drainage system

The purpose of a drainage system is to remove water and provide an aerated root zone, however, the required aerated depth will vary with the season and crop growth. If a drainage system is installed and not controlled the effectiveness of a water management plan using shallow ground water may be reduced because insufficient water is available to meet crop demand. Doering et al. (1982) defined this as over drainage or a condition when uncontrolled drainage flow increased the depth to water to the extent that is was of limited use to crops. For crops to effectively use shallow ground water, the water table will have to be maintained at a pre-determined depth. The drainage laterals also need to be installed perpendicular to the surface grade of the field to insure that water table control is possible on the entire field (Ayars 1996)

The ideal water table control scenario would be to have the water table close to the bottom of the crop root zone early in the season and have it recede as the root zone develops. This should maintain a relatively constant distance between the bottom of the root zone and the saturated zone. This conceptually would permit the maximum use of water by the crop from the shallow ground water. The distance will depend on the soil type, close with sand and progressively larger for the finer textured soil, and the irrigation system and its management. Systems with poor uniformity and potential for large amounts of deep percolation would require greater distance between the root zone and water table.

The source of the water creating the shallow ground water will also determine the effectiveness of any management system developed to utilize ground water. If shallow ground water results primarily from deep percolation loss due to poor irrigation practices, improvements in irrigation efficiency will reduce the water being contributed to shallow ground water and will reduce the potential usefulness. If the shallow ground water is being sustained by lateral regional flow from inefficient irrigation, channel leakage, and rainfall, then there is a potential for sustained water use from shallow ground water.

In regions with saline ground water, the potential for sustained ground water use will be limited by salt management in the soil profile particularly in the root zone. Salt management is often accomplished during a fallow period between crops by irrigating prior to planting to refill the depleted soil water and to leach accumulated salt. This technique has been termed preplant irrigation and has been used effectively in the San Joaquin Valley of California and in other arid regions of the world (Ayars 2003). Salt management is possible with monsoon rain in those areas with this type of climate (Sharma 1998)

Irrigation system and management

Irrigation system management has a direct impact on the potential for crop water use. This includes the depth of application, the uniformity of application, and the frequency of application. Surface irrigation methods, such as flood, furrow, and basin, generally apply large volumes of water in short periods of time and may have a low application frequency. Unless these systems are well designed, installed, and managed there may be poor distribution uniformity with excessive deep percolation losses resulting in waterlogging, loss of production, poor crop health, and excess additions to shallow ground water in some areas and under irrigation in others. In fields with controlled drainage there is the potential for redistribution of the groundwater through the subsurface drainage system that will contribute to the ground water in the under irrigated areas. As a result, the under-irrigated areas may have more crop water use from shallow ground water than the over-irrigated portions of the field. However, on the whole there will be less crop water use than if the crop was uniformly irrigated.

Irrigation frequency and the depth of water applied to replenish lost soil water are major determinants in the volume of water extracted from shallow ground water. Research done by Benz et al. (1978), Benz et al. (1981), Benz et al. (1982), and Benz et al. (1987) demonstrated the effect of depth of application on water use by alfalfa, corn, and sugar beet from shallow ground water. The data in Fig. 2 show the shallow ground water use data from an alfalfa experiment that replenished soil water on a weekly basis at rates of 0.3, 0.8, and 1.3 times ET. The data show that the ground water contribution increases as the level of replacement decreases. The majority of crop water use from shallow ground water occurred at the end of the irrigation interval just prior to the next irrigation. The maximum soil water potential gradient had developed at this time resulting in the largest contribution. If the interval is reduced or the depleted soil water is completely replaced there is little or limited opportunity for the crop to use water from the water table. This means that high frequency, daily or near daily irrigation, reduces the potential water uptake from shallow ground water. Twice weekly or weekly irrigation after the crop has reduced the soil water content in the soil profile seems to maximize the potential for crop water use from shallow ground water (Hutmacher et al. 1996).

Irrigation scheduling in the presence of shallow ground water to induce crop water use remains a problem. Ayars and Hutmacher (1994) developed crop coefficients (K_c) for cotton as a function of depth to ground water and salinity of ground water that can be used to schedule irrigation of cotton in the presence of shallow saline ground water. The coefficient effectively extends the irrigation interval and accounts for soil water extraction and upflux from the ground water. Several of the coefficients are given in Fig. 3. These data demonstrate several aspects of the problem associated with managing irrigation in the presence of shallow ground water and trying to increase the crop water use from shallow ground water.

The amount of crop water use from shallow ground water is characterized by the difference between the base curve and the curve representing ground water quality and depth to ground water. The base curve is equal to ET extracted from stored soil water without any contribution from ground water. As more water is taken from ground water the distance increases between the base K_c curve and the K_c curve characterizing the depth to water and the ground water quality. Note that early in the growing season there is no difference between the K_c curves and there is no contribution to crop water use from the water table. As the plant and root system develop the distance between the curves increases as does the ground water contribution denoted by the difference in K_c values. The maximum contribution occurs late in the growing season and in surface irrigation after the last irrigation of the season.

The curves for EC= to 0.3, 7.7, and 15.4 dS/m at 1.1 m depth demonstrate that the potential crop water

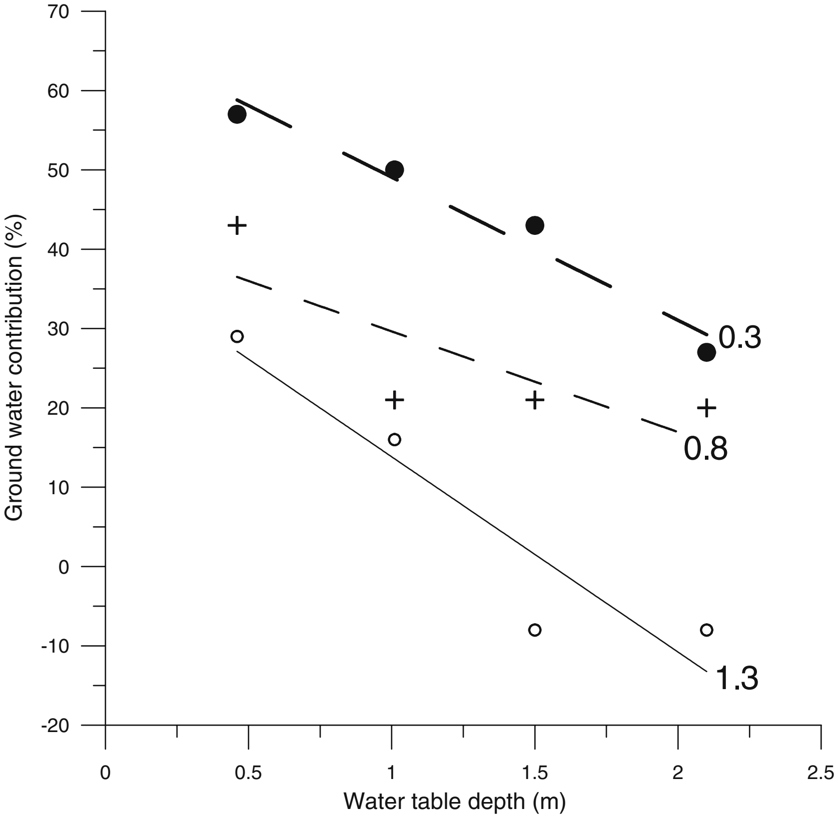


Fig. 2 Ground water contribution to alfalfa crop water use in response to irrigation levels. After Benz et al. (1987)

use from shallow saline ground water is the same up to approximately two times the Maas–Hoffman threshold (7.7 dS/m) before yield reduction occurs in cotton. The curves were developed using good quality irrigation water, so the salinity in the root zone is maintained below the threshold value. As the salinity in the soil profile increases the potential in the ground water is higher than in the soil water, and the plant is still capable of extracting up to the maximum required.

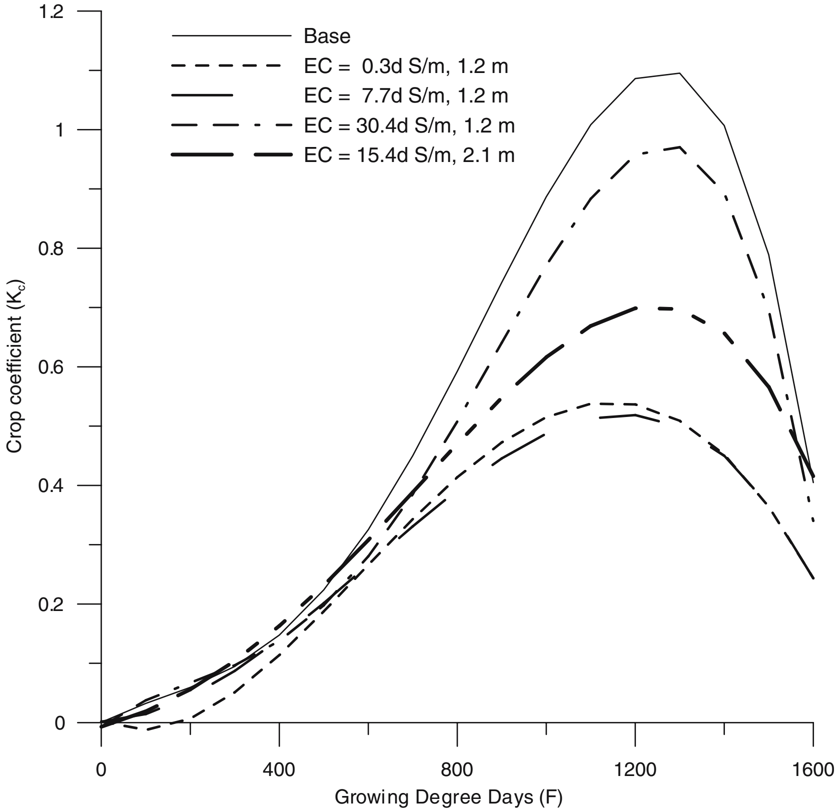
As the salinity increased to four times the Maas–Hoffman threshold the crop water use from the ground water was significantly reduced but not eliminated. Note also, that the crop water use was reduced even when the ground water salinity was 15.4 dS/m when the depth to ground water was increased from 1.1 to 2.1 m. In this situation the reduction was a result of the increased distance between the water table and the effective part of the root zone and the additional time for the root zone to develop.

Discussion

Much of the research related to crop water use from shallow ground water has been done under field conditions (Kruse et al. 1985, 1993; Follett et al. 1974; Benz et al. 1978, 1981) and the water table contribution to the crop water use was calculated as a closure term in the water balance equation. The limitations to this approach are the accurate characterization of the crop ET, the variability of the soil, and the depth to the water table. In the studies by Benz et al. (1978) and Benz et al. (1981) the water table was not constant and the estimates were made with a variable depth to the ground water that also affected the total contribution. The water balance calculation also required an estimate of the change in stored soil water. With the advent of new technologies, (TDR, capacitance probes) for soil water measurements there are options for improving this component of the equation. When possible, field studies will probably provide the most realistic data for crop water use from shallow ground water but finding sites that are suitable for this type of research is a problem. An ideal site is one that has a water table that doesn't fluctuate or that can be controlled, that has soil that is not to saline, and is large enough to be representative of the area.

Lysimeters, weighing and drainage, have also been used to study crop water use from shallow ground water. Lysimeter studies have the advantage of good control on most of the variables in the water balance equation. The water table is generally controlled at a fixed depth during the experiment which eliminates one variable in the interpretation of the results. The water fluxes to the soil mass and from the soil mass can be accurately measured. With a weighing lysimeter the ET can be measured accurately while soil water measurements are required for a drainage lysimeter. In either case, the effect of soil variability on the result is minimized. However, lysimeters are expensive to build and maintain and are often not representative of the field conditions for the crop.

Fig. 3 Cotton crop coefficients as a function of ground water quality and depth to ground water. after Ayars and Hutmacher (1994)



Care needs to be taken to insure that the lysimeter is surrounded by a crop having similar characteristics. If this is not the situation then the ET will not be representative of the field condition.

The water table in the cited studies ranged from 0.5 to 2.9 m with most of the research focusing on depths from 1.0 to 1.5 m. The depth selection was made in response to the crop being used and the overall objective of the study. Oftentimes, the results were reported from field studies that included fertilization and little or no irrigation. The shallow depths were used on shallow rooted crops and crops that tolerated waterlogging. The depth to water table increased for crops with deeper rooting systems. It should be possible to increase the water table contribution if a variable water table depth could be studied. In this case the crop has access to the water table earlier in the growing season since the distance between the water table and the root system is minimized. However, this is not typical of field conditions because there is very little control of the water table possible under field conditions. Additional work is needed to develop control of the water table in the field.

All types of soil were used for researching crop water use from shallow ground water. The selected soil was generally the predominate soil type in the area and the one that was used for the crops being studied. The maximum crop water use was generally from the loam soils, (sandy loam, fine sandy loam, clay loam). As the clay content increased, the percentage contribution was reduced as a result of the reduced hydraulic conductivity with increased clay content, as demonstrated in Fig. 1.

Irrigation management is one of the major factors confounding the quantification of the potential for crop water use from shallow ground water. Most experiments adopted a fixed irrigation schedule to simplify the operation and there was no guarantee that the maximum contribution would be achieved. In the studies in North Dakota, Benz et al. (1978), Benz et al. (1981) irrigated weekly using a water budgeting procedure that estimated crop water use based on ET and a crop coefficient, rainfall, and change in soil water. Irrigation was applied as a percentage of the total ET in the previous week (Fig. 2).

The data show that with a shallow water table there is some ground water contribution even with over irrigation. The ground water contribution increases as the percentage replacement is reduced. The percentage ground water contribution increases at a specific depth as the irrigation quantities are reduced, as would be expected. The higher levels of crop water use with reductions in applied water are in response to increased matric potential gradients in the soil from the water table to the root zone.

Results from Ayars and Hutmacher (1994) and Wallender et al. (1979) demonstrate the need to establish a soil water potential gradient in the profile to induce water use from shallow ground water. This requires a period of water depletion prior to irrigation but not the extent that plant stress becomes excessive. Kite and Hanson (1984) demonstrated the use of leaf water potential in cotton as a methodology to schedule irrigation that included the crop water use from shallow ground water.

A study conducted on the west side of the San Joaquin Valley of California is a good example of the potential for use from shallow ground water (Ayars et al. 2001). A cotton and tomato rotation was grown in a field having a shallow saline (6 dS/m) ground water that ranged in depth from 0.6 to 2 m during the year. The crops were grown with surface irrigation and subsurface drip irrigation (SDI). In 1 year of the project approximately 40% of the 690 mm water requirement for cotton was taken from shallow ground water. This was in plots irrigated using SDI. The furrow irrigated plot had approximately 40% of the 645 mm water requirement met by in-situ ground water use. In both cases the irrigation was scheduled using a modified crop coefficient that accounted for crop water use from shallow ground water. Irrigation was initiated after some plant water stress was established.

The Meyer equation (Wu 1999) Eq. 2 can be used to demonstrate the interaction of soil type, soil water content, and depth to water table on crop water use from ground wate. The ratio of upflux to ET (U/ET) was calculated for depth to water table (*x*) and for the ratio of the distance from 1/3 of the root zone depth to the depth of the water table (Z_r/Z_m) where the upflux is equal to 1 mm/day. These data are given in Fig. 4. The data demonstrate that the maximum upflux will occur with a dry root zone and shallow ground water and that the minimum will occur with a dry root zone, and a wet root zone with either a deep or shallow ground water. In the case with shallow ground water and wet root zone, water use is probably being affected by water logging and evaporation from the soil surface.

A goal of this review was to develop a methodology to determine if crop water use from shallow ground water is an appropriate water management option for a particular site and to assist in considering management alternatives. The methodology involves an analysis of the existing soil and water conditions in the context of the proposed cropping patterns. The data described in Table 3 are used to analySe the feasibility of using shallow ground water as a supplemental water supply and to select suitable crops and management.

Ratios were developed using the crop, soil, and water data to guide the evaluation of a cropping pattern for a given site. These were developed based on the literature and field experience and are summarized in Table 4. The significance of an individual ratio will have to be weighed as one factor in the decision making process.

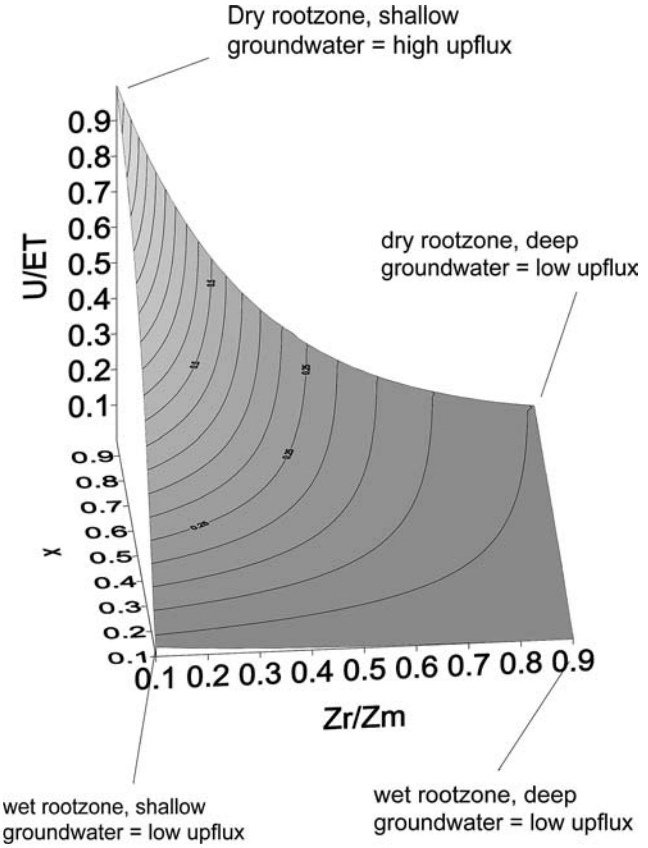


Fig. 4 Ratio of upflux to evapotranspiration calculated using the Meyer equation

The objective is to select a crop that will have an extended period of time to use water from shallow ground. This will require the root zone to be in close proximity of the water table for an extended period and that the crop growth will not be limited by salinity. This resulted in the following ratios being developed for crop selection. The ratio of the EC of the ground water to the Maas–Hoffman threshold for yield reduction should be ≤ 2. This will match the salt tolerance of the crop to the EC of the ground water to maximize potential use. The number of days for maximum root development to total growing period should be <0.5. This will maximize the opportunity time for the crop to use water from shallow ground water. The maximum rooting depth divided by the average water table depth (top of capillary fringe) should be >0.5. The effective water extraction depth divided by the water table depth should be <0.4 if the Meyer equation ratio Z_r/Z_{max} is used. This will position the root zone close to the water table and maximize potential flux.

Any type of irrigation system can be used successfully in the presence of shallow ground water provided it is managed properly. This requires that the selected system be capable of the required frequency of application with a good uniformity. In soils that store large amounts of water, the irrigation frequency may be reduced without a significant adverse impact on yield. Most irrigation systems will work provided they are well designed, constructed, and managed. However, in soils that have limited storage capacity (coarse textured), an irrigation system capable of higher frequency irrigation would be required, i.e. sprinkler or

Table 3 Data needed to characterize suitability of cropping pattern for in-situ use of ground water by crops

Ground water—Salinity, boron concentration, source of ground water (deep percolation, lateral flow), depth to ground water, initial and final depths to ground water and rate of change, average depth to ground water
Crop—Annual, perennial, salt tolerance, total water requirement (ET_c), days to maturity, total growing period, response to stress, drought, or oxygen stress, rooting depth (see Borg and Grimes 1986), days to maximum rooting depth, total growing period for crop, annual, perennial, tap, fibrous
Irrigation system and management—Type of system, irrigation frequency, irrigation depth, irrigation water quality
Drainage System—Presence of drainage system, configuration (depth of laterals, lateral spacing, lateral position relative to surface grade), gravity, pumped
Soil Type—Clay, loam, silty clay loam, etc

Table 4 Parameters used to evaluate suitability of site for in-situ use of ground water by crops

Ratio	Value
EC (ground water)/Maas–Hoffman threshold for yield loss	≤ 2
Days to maturity/Total growing period	< 0.5
Maximum rooting depth/average Water table depth (top of capillary Fringe)	> 0.5
Effective extraction depth/Water table depth when using Meyer equation ratio Z_r/Z_{max}	< 0.4

drip. These soils would also have to have a shallower ground water (< 1 m) to maximize the potential crop use.

Conclusions

The research summarized in this paper highlights that shallow ground water is potentially a valuable source of additional water supply to meet crop water requirements in humid, arid, and semi-arid conditions. However, the application of this technique is site specific and requires a detailed analysis of the projected cropping patterns, the soil and water resources, and irrigation management. The practice will be limited by the source of water supplying the ground water, the management of salt and other elements in the soil profile. This practice is possible in both drained and undrained areas. However, it should be carefully considered before application in undrained areas affected by shallow ground water because salt accumulation in the root zone will be harder to manage.

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