# SALINITY, DRAINAGE AND CROP PRODUCTION IN IRRIGATED AGRICULTURE

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## Introduction

Soil salinity is the most prevalent and widespread problem in irrigated agriculture. It has, therefore, attracted the attention of the scientific community since the advent of modern agronomic research. Thorough the past seven to eight decades a considerable body of information has been accumulated, which has promoted the understanding of the principles involved and helped to promote the technology of coping with the problems. Our present knowledge, if judiciously applied, is adequate to deal with the many problems resulting from the mismanagement of irrigation and drainage.

One of the major causes of salinity in irrigated agriculture is inadequate drainage. Most irrigation systems run with a certain degree of inefficiency, resulting in inevitable drainage beyond the root zone. Since 80% irrigation efficiency is considered as reasonably good, 10% deep percolation and leaching can be expected under the best irrigation practices (excluding drip/trickle irrigation). This level of leaching is adequate for salinity control under ordinary irrigation conditions. But when natural drainage is limited, a rise of the water table may be expected. With the majority of gravity irrigation systems the inefficiency of water application is generally much lower, resulting in more severe conditions. Additionally, water conveyance systems (usually unlined canals) will lose water through seepage, further aggravating the problem.

A rise in the water table level to within the root zone, without adequate drainage will result eventually in salinization of the soil above the water table. The degree of salt accumulation will depend mainly on the depth to the water table and its salt concentration, soil hydraulic properties, and rainfall amounts and distribution. Under conditions of a stationary water level the maintenance of a deep water table (usually below 1.8 m) is desirable in order to prevent the accumulation of hazardous level of salts in the root zone.

Installing a man-made drainage system can alleviate the adverse conditions of poor drainage. When a drainage system is installed and operating, a net downward flux of water is established and leaching will take place preventing long term accumulation of salts. Under such conditions, the desirable depth to the water table is no longer influenced by the upward movement of salts, but will depend mainly upon the need to provide a sufficiently deep, aerated root zone. The hydraulic conductivity of the soil must be high enough to allow sufficiently rapid leaching to take place.

The process of salt accumulation is intimately connected with the process of evapotranspiration. As water is taken up by the crop and evaporates from the soil surface, the salts are left behind and accumulate. The maximum level to which salts can accumulate depends on their solubility. The maximum level can be reached only near the soil surface where water loss through evaporation predominates. In the soil layers where water loss through transpiration predominates, the maximum level of salt accumulation is that against which roots can still absorb water. Controlled leaching will assure that this concentration is present at the bottom of the root zone.

Leaching may be considered the key to successful agriculture under irrigation. It controls all aspects of salt accumulation in the soil (concentration, precipitation, exchange and dissolution), it influences the drainage requirements and ground and surface water quality, and it interacts closely with crop response. Reducing the intensity of leaching will result in salt accumulation at shallower depths, causing ever decreasing rooting depth. But the maximum salt concentration will still stay the same (Fig 1). Thus the maximum concentration to which salts can accumulate in the soil depends on the salt tolerance of the crop in question, rather than on the leaching fraction (LF).

## Water table depth, water logging and crop response

Analysis of field and lysimeter experiments reported in the literature from the USA, The Netherlands and Israel provide information on optimum water table depths for the maintenance of good aeration for some specific crops. Often, the relationship between crop yield and water table depth is curvilinear with yield increase becoming smaller as the water table depth increases. We used a linear regression analysis on the steeply changing part of the curve, up to 90% of maximum yield, and the results are given in table 1. Table 1 refers to data obtained on medium to fine textured soils where crops were kept well watered by irrigation. For coarse textured soils permissible levels may be shallower, e.g. 30 to 40 cm for maize and snap beans, respectively (Goins *et al.* 1966). The depth to the water table for optimum crop yield ranges from 0.60 to1.05 m with mean depth of 0.83 ± 0.14 m, provided that salinity and soil fertility are not limiting. The rate of yield decline as water table level is raised ranges between 40 and 150% per m, with a mean of 100 ± 40% per m.

As a result of expert consultation, the FAO (1980) published recommendations for optimum water table depths for irrigated soils. Under non-steady state conditions the suggested water table depth during the irrigation season for field crops and vegetables was 90 cm on both fine textured and coarse textured soils. This is similar to results presented above. Under steady state the recommended depths were 110 to 120 cm for fine textured and 100 cm for coarse textured soils. In order to prevent soil salinization during the off season period, the recommended depths were greater (100 to 120 cm for transient state and 130 to 140 cm for steady state conditions).

Most crops, except those specifically adapted, such as rice and some grasses, can not tolerate water logging (the presence of water at or above the soil surface) for more than two to three days without some damage. Some crops, e.g. wheat (Meyer and Barrs 1988) are more tolerant to water logging than others, e.g. maize (Mason *et al.* 1987).

Two factors may significantly alter the above relationships - the nitrogen cycle in the soil and the accumulation of salts in the root zone above the water table.

## Nitrogen supply and drainage conditions

When aeration is poor, the process of denitrification is accelerated and mineralization and nitrification is decelerated. The result is loss of nitrogen from native soil storage and from applied fertilizer. According to Zwerman and Corpus (1965), a normal nitrogen supply of 60 to 100 kg/ha in well-drained soils may be reduced to 20 to 30 kg/ha when water table level is raised to 0.30 m depth.

Some reports are available regarding the interactive effect of N supply and poor drainage conditions on crop growth. Visser claims that under Dutch conditions a water table depth of 0.60 m is sufficient for adequate aeration and optimum plant growth. Thus, according to him less than optimum yield is obtained with water table position deeper than 0.60 m, mostly because of N deficiency as a result of N losses, rather than from direct effect on root anoxia, assuming adequate water supply.

Van Hoorn (1958) found that of the total yield reduction of grain crops due to water table level change from 1.50 to 0.40 m, 24% was due to the direct effect of poor aeration on the crops and 76% to the effect of poor aeration on N supply. By adding N fertiliser to a soil with water table levels at 10 and 30 cm, Shalhevet and Zwerman (1962) obtained yield increases of 34 and 39%, respectively. By lowering the water table to 1.30 m yield was improved by 91 and 67%, respectively. Thus, N fertilization accounted for 37 and 58%, respectively of the total change in yield due to improved drainage. When Lal and Taylor (1969) lowered the water table level from 15 and 30 cm to well below rooting depth, they obtained 61 and 43% increases in yield, of which N availability accounted for 28 and 53%, respectively. Table 2 summarizes these results. In general, the proportion of yield reduction due to N deficiency in conjunction with poor drainage increased as drainage conditions were improved to a point where all the reduction in yield was due to N deficiency.

Meyer *et al*. (1987a, b) studied the nitrogen response of maize and cotton under conditions of flooding for various durations following irrigation. Of the total yield decline of maize of 42%, 32% was due to poor aeration and only 10% to lack of N. Thus N deficiency was responsible for 24 % of the total yield decline due to water logging. With cotton, of the total yield decline due to water logging of 74%, 82% was due to N deficiency. Since

N deficiency is clearly an important factor in the deleterious effect of poor aeration, Hodgson and MacLeod (1987) attempted to overcome the effect by spraying a cotton crop with liquid urea at the rate of 20 kg/ha/irrigation before each period of 16 hours of inundation. They obtained a 40% increase in yield with N spraying alone, while reducing the period of inundation every irrigation from 16 to 4 hours, without spraying resulted in a yield increase of only 15%.

## Crop response to salinity

### a. General Response

A considerable amount of data is available regarding the effect of soil salinity, as expressed by the electrical conductivity of the soil solution ($EC_s$) or of the saturated soil extract ($EC_e$), on crop yield. Most of the data was obtained under uniform spatial and temporal distribution of salts, at high levels of fertility and with the crop established prior to the introduction of saline conditions. Maas and Hoffman (1977) and Maas (1986) summarized the data of various authors. Figs 2 and 3 were drawn from the data provided by Maas (1986) for field and vegetable crops. These data relate soil salinity as expressed by the electrical conductivity of the soil saturation extract ($EC_e$) to fractional yield ($Y_r$). The general relationship is presented in fig 4 and can be expressed by the equation

$$Y_r = 1 - (EC_e - t)\, s$$

Where (t) is the threshold salinity where yield just begins to decline and (s) is the rate of yield decline with increasing salinity. Salt tolerance is characterized by the values of both the threshold and slope. Tolerant crops such as cotton, barley, sugar beet and asparagus have
high threshold value and small slope, while sensitive crops such as bean, onion, carrot and strawberry have low threshold and large slope.

In practice, under realistic field conditions, uniformity is the exception rather than the rule, soil fertility may not be optimal, and salinity may be present before the crop is established. In addition, crops may have differential sensitivities at different stages of growth. Are these changes significant with respect to the application of salt tolerance ratings to a variety of field conditions?

### b. Interaction with soil fertility

Nitrogen (N) - Three types of relationships between the level of nitrogen application and salinity may be expected: (i) the addition of N results in the same relative yield increase at all levels of salinity; (ii) there is a larger increase in relative yield due to N application at low than at high salinity levels; (iii) there is a larger increase in relative yield due to N application at high than at low salinity levels. When type (iii) response occurs, N, in fact, alleviates to some extent the deleterious effect of salinity on yield.

Table 3 is a summary of studies on salinity-fertility interaction. Out of 51 reports only in five there was more positive response to fertilizer under high than under low salinity. Out of the rest, half showed similar response to fertilizer at all levels of salinity and half showed more positive response under low than under high salinity. Thus, by far the most common types of relationship reported in the literature are (i) and (ii). Apparently, plants are more sensitive to salinity when conditions are conducive to high yields. At extremely low soil fertility increase in salinity has very little additional damaging effect on yield.

Phosphorus (P) - The interaction of P nutrition and salinity is complex. In addition to the three types of response described for N interaction, for some crops under some experimental conditions, added phosphate to the growth substrate under high salinity conditions may be very detrimental. High salinity induces phosphorus toxicity. This phenomenon occurs mainly in solution culture experiments. Under field conditions of high salinity the concentration of Ca in the soil solution is normally high enough to result in the precipitation of P with Ca, resulting, normally in high P fertilizer requirements.

Potassium (K) - Most crop plants have a very high selectivity for the absorption of K over Na. Only under conditions of very low Ca concentration (less than 10 me/l in solution) can this selectivity be disrupted. Such conditions occur mainly in nutrient solution cultures high in NaCl. Consequently, although plants grown in high-Na substrate containing sufficiently high Ca concentration exhibit reduced uptake and translocation of K, there is paucity of data to show a stronger positive response to K fertilization under high salinity conditions than in non-saline soils. In fact, frequently plants exhibit a greater sensitivity to high concentration of KCl than to NaCl, when these salts are applied as single salt solutions (Weimberg *et al.*, 1984).

c. Non uniform salinity distribution within the root zone and in time

Under normal field conditions, when a certain low degree of leaching is provided, at steady state conditions salinity will increase with depth, with the maximum concentration occurring at the bottom of the root zone. During transient conditions the maximum concentration may be located at any depth within the soil profile. When soil evaporation is high, there will be some accumulation at the surface soil layer. When a shallow water table exists, there is a tendency for salinity to increase towards the soil surface. Only under conditions of very high leaching does a uniform salinity profile develop, as was the case in most of the experiments designed to obtain salinity response functions. What would constitute an effective mean salinity under non-homogeneous conditions?

The bulk of evidence so far indicates that the mean salinity with depth, integrated over time is the most representative effective salinity. Table 4 presents results of five experiments designed specifically to test the effect of non-uniform distribution of salts on crops. The best correlation with yield was obtained for the mean electrical conductivity of either soil water ($EC_{sw}$) or saturated paste extract ($EC_e$). In the case of the experiment by Ingvalson *et al*. (1976), where salinity was measured frequently using salinity sensors, the time integrated $EC_{sw}$ gave the best results. The results of Bower *et al* (1970) and Shalhevet *et al.* (1969) are of soil salinity values varying widely (2 to 3 fold) with depth, with maximum values occurring at the bottom and the top of the root zone, respectively

Hoffman *et al.* (1983) conducted an experiment on an organic soil comparing the effect of salinity on sub-irrigated and sprinkler-irrigated maize. The response function to the mean soil water salinity was similar for both irrigation methods, independently of the greatly variable salt distribution in the root zone between the two methods.

Generally speaking the duration of exposure to salinity during the season will determine the extent of the salinity damage (table 5). The later was salinity introduced the lower was the damage (higher salinity at which yield was reduced by 50%). However, when yield was related to time weighted salinity a uniform relationship emerges regardless of when salinity was applied. A notable exception is the seedling stage of growth, when the plants are specifically sensitive to salinity. For this reason in most of the salinity tolerance experiments treatments were applied only after plants were established.

Although salinity delays germination and emergence, most crops are capable of germinating at higher salinity levels than they would tolerate at later stages of growth. For example, peanut was shown to germinate well under high salinity, but subsequent seedling growth was severely restricted. The 50% reduction in percent seed germination was at 13 dS/m, while seedling growth was reduced by 50% at 7.5 dS/m. Final crop yield proved to be very sensitive to salinity (50% seed yield reduction was at 4.7 dS/m, Shalhevet *et al.*, 1969).

d. Climatic factors

Three elements of climate – temperature, humidity and rainfall – may influence salinity response, of which temperature is the most critical.

Temperature - High temperature increases the stress level to which a crop is exposed, either because of increased transpirational demand or because of the effect of temperature on the biochemical transformations in the leaf. The increase in the level of stress due to high temperature increases the sensitivity of the crop to salinity. Ehilig (1960) found injury due to chloride leaf burn in grapes to develop much more rapidly at air temperatures greater than 38 $^oC$ and very slowly at temperatures below 32 $^oC$. $CaCl_2$ treatments were much more injurious than NaCl treatments.

Magistad *et al.*, (1943) tested beans, squash, sugar and garden beets, carrots, cotton, onion and tomato, at three locations in California each having a distinctly different climate. They concluded that the yield of the crops was depressed more in warm than in cool climate. For example, an osmotic pressure of 0.41 MPa caused onion yield loss of 80% at Riverside where the mean maximum temperature was 36 $^{o}$C, but only 10% at Torrey Pine where the temperature was 25 $^{o}$C. Beans were not so strongly affected. At 0.24 MPa osmotic pressure the reduction in yield at Riverside was 63% while at Torrey Pine it was 50%. Hoffman *et al.*(1978) found a 94% reduction in Pinto beans (Phaseolus vulgaris L.) yield due to an osmotic potential of -0.2 MPa at 32 $^{o}$C while only 38% yield loss at 26 $^{o}$C mid-day temperature.

Humidity - High atmospheric humidity tends to decrease to some extent the crop stress level, thus reducing salinity damage (Gale *et.a*l., 1967 for bean; Hoffman and Rawlins 1971 for radish and onion). Cotton yield at 90% RH was about 10% of the yield at 65% RH (Hoffman et al., 1971). Nieman and Paulson (1967) found high humidity to completely relieve the suppressive effect of salinity of OP = -0.3 MPa on the yield of cotton, though high humidity depressed yield to some extent under both conditions, as is the case with most other crops.

Rainfall – Rainfall has no direct effect on the salinity response function, except inasmuch as high rainfall increases leaching thereby permitting the use of water of higher salt content than would otherwise be possible.

e. Interaction of salinity and poor drainage

It is obvious that both poor drainage and salinity reduce crop yield and the effect is additive. It is not clear, however, whether the effect is also interactive. That is, does the change in the level of one variable influence the response to the other.

Two types of responses were observed. With a type I response deteriorating drainage conditions caused salinity tolerance to improve and a type II response where deteriorating drainage conditions caused salinity tolerance to impair. A summary of result is presented in table 6.

Type I response: In a lysimeter experiment with wheat ( Chaudhary *et al*. 1974 ), as water table level changed from 1.20 to 0.60 m, the $EC_e$ at which yield of wheat was reduced by 50% increased from 10 to 18 dS/m, showing an improvement in salt tolerance. The same type of result was obtained with maize using solution culture either aerated or bubbled with N gas (Drew *et al.* 1988) and with sultana grapes using sand cultures (West and Taylor 1984).

Type II response: In a lysimeter experiment with soybean (Williamson 1963), as water table depth decreased from 0.75 to 0.15 m the $EC_e$ at which yield was reduced by 50% decreased from 8.8 to 2.8 dS/m showing a decrease in salt tolerance. The same type of response was obtained with alfalfa by Bernstein and Francois (1974) comparing suction drained and gravity drained lysimeters using a high leaching fraction (LF=0.5). The $EC_e$ at which the yield was reduced by 50% was nearly 1.5 times greater in the suction lysimeter (good drainage) than in the gravity lysimeter (poor drainage). West and Taylor (1984) demonstrated this type of response with shiraz and some other varieties of grapes, as well as with beans (West and Taylor 1980).

The upward movement of shallow groundwater and its subsequent evaporation at the soil surface leads to salinization. To minimize the rate of salt accumulation artificial drainage is normally installed to lower the water table. The depth of the water table, soil properties and the rate of upward movement must be known to establish the appropriate depth to maintain the water table.

Starting from a wet soil, the drying rate at the soil surface is first controlled by the evaporative demand of the atmosphere. As the soil surface dries, the evaporation rate becomes limited by reduced water transmitting properties of the soil. Under arid conditions this situation is reached rapidly.

Gardner and Fireman (1958) developed the following relationship between soil hydraulic conductivity (K) and soil water suction (S), which is a function of soil water content

$$K = a / (S^n + b)$$

Where a, n, and b are constants. For many soils values of n equal to 2 or 3 fit experimental values well. Figure 5 gives the theoretical maximum rate of upward flow from a stationary water table for two soils as a function of the depth to the water table. According to this figure, lowering the water table from the surface to 1 meter for clay or 1.5 meter for sandy loam soil will be of little benefit as the upward movement of water and salt is still too excessive. Further lowering the water table to 2 to 2.5 meters reduces substantially the upward flow, but beyond these depths the change in upward flow becomes insignificant.

The above discussion applies to a stationary water table. When an appropriately designed drainage system is installed a net downward flux of soil water is maintained and leaching occurs. In this case ground water salinity loses its significance as a criterion determining the desired depth of drainage. The main criterion becomes the need to maintain a sufficiently deep aerated root zone. This depth is typically about 1 meter, as indicated in section 2 above, specifying a drain installation at 1-1.5 m.

## Irrigation practices for salinity control

Irrigation scheduling is the major practice that may be modified in order to facilitate salinity control. Scheduling consists of two aspects - quantity of water to be applied and irrigation interval. The choice of irrigation method also has consequences with respect to the control of salinity.

a. Irrigation water quantity and leaching requirement

The quantity of water to be applied to a crop to obtain optimum yields depends on the water requirement (consumptive use) of the crop under a given climatic condition and the leaching requirement to prevent salt accumulation in the root zone. It is difficult to separate under field conditions the consumptive use requirement from the leaching requirement. This is because irrigation efficiency is never perfect and the estimation of the water requirement using climatological methods or by direct measurements is subject to considerable error. Consequently, in order to obtain maximum yield, irrigators normally apply more water then the minimum needed in consideration of low efficiency, a practice that results in passive leaching.

It has been amply shown that the water production function, that relates yield to applied water, does not depend on salinity. The level of soil salinity causes a decrease in the maximum yield (yield plateau) concomitantly with a reduction in consumptive use but not the slope of the relationship. Fig 6 is a typical example. The combined relationship of relative evapotranspiration ($ET_r$) to soil salinity ($EC_e$) and yield may be expressed by the following equation

$$ET_r = 1- (s/c)\ (EC_e - t)$$

where c is the slope of the water production function and s and t are the slope and threshold salinity from the salinity response function. Obviously, as salinity increases ET decreases and the water requirement for maximum yield, as well as the maximum yield decreases. When yield and consumptive water use is reduced due to salinity increase, continuing normal irrigation practices will result in considerable leaching. The above hold as long as irrigation efficiency is high. When uniformity of irrigation water distribution is poor and deep seepage takes place the slope of the production function may become curvilinear. This is also true when intentional leaching takes place (Fig 7).

With drip irrigation water is applied from a point source resulting in high leaching near the emitter where root concentration is high and, thus, in low salt concentration, except at the wetting front. Leaching will need to be applied before subsequent crops are planted.

Seasonal rainfall will also result in leaching. The efficiency of leaching by rain depends on the water holding characteristics of the soil. A sandy soil with field capacity of 15% (15cm water per 100cm soil) will be completely leached by 30 cm of rain, while a clay soil with field capacity of 40% will be only partially leached.

b. Irrigation interval

As soil dries between irrigation, both the osmotic and the matric potential decrease. The rates at which these processes occur depend on ET and on the water desorption properties of the soil. Shortening the interval between irrigation causes higher pre-irrigation soil water content and a lower pre-irrigation salt concentration; both features enhance plant growth.

Intuitively, one expects this favorable effect to be greater for saline than for non-saline soil. However, several processes occur which result in a smaller response to irrigation interval under saline than under non-saline conditions. More frequent irrigation result in an upward shift in the depth of the peak sat concentration into region of greater root concentration (Bernstein and Francois, 1973b, fig 8). Under sprinkler irrigation, increasing the irrigation frequency may result in more severe leaf burn as a result of frequent wetting of the foliage.

More significant, however, is the fact that salinity reduces ET, resulting in slower rate of soil drying. Consequently, for the same irrigation interval the total pre-irrigation soil water potential (matric plus osmotic) may be lower, causing greater yield reduction under non-saline than under saline conditions (fig 9). In this case reducing irrigation interval will be more beneficial under non-saline than under saline conditions.

Field experiments in three different soils and two ecological regions of Israel tested the impact of irrigation interval and irrigation water salinity on eggplant (Shalhevet *et al,* 1983) and corn (Shalhevet *et al*, 1986). A unified function of relative yield versus mean root zone salinity could be used for both crops for all irrigation intervals tested. The results of the corn experiment are presented in fig 10 for irrigation intervals from 3.5 days to 21 days. Most studies reported in the literature show no benefit, or even damage of decreasing the irrigation interval under saline conditions.

c. Irrigation method

Irrigation methods differ in the way they interact with salinity. Each method has specific advantage and disadvantage for salinity management. Gravity irrigation include flood and furrow irrigation. Wild flooding and border method are inherently not uniform in water application and are not suitable for salinity control. The basin method has the potential for more uniform water application than other flooding methods provided the basins are leveled, sized properly, and have uniform soils.

The principle problem with furrow irrigation is the accumulation of salts in the seedbed while leaching takes place in the furrows (fig 11). This may result in uneven seed germination. This can be overcome by planting on the side slopes of the beds, planting in the furrows, etc. (Bernstein and Fireman, 1957). If the surface soil is mixed between crops the long term increase in soil salinity may not be serious. When it is, leaching must be applied using other irrigation methods.

Well designed sprinkle irrigation provide relatively uniform salt and water distribution (fig 11), but is unavoidably accompanied by wetting of crop foliage unless under canopy irrigation is possible (e.g. with tree cops). Salts can be absorbed directly into the leaves; thus some crops experience foliar injury and yield reductions that may not occur when they are surface irrigated with the same water (Maas et al, 1982). Injury is crop specific, some cops being more sensitive than others (Table 7). Intermittent sprinkling such as with the impact sprinkler frequently causes more injury than continuous sprinkling. This is attributed to salt accumulation on the leaves when water evaporates between wetting events. It is recommended that sprinkling is done at night as foliar injury is more acute when sprinkling is done during the heat of the day when evaporation is high.

The introduction of trickle/drip irrigation revolutionized the use of brackish water for irrigation. The advantage if drip irrigation is twofold. In the first place leaf injury is avoided and for sensitive crops such as potato, pepper and tomato it may make the difference between success and complete failure. For example, yield difference of 50% was found for bell peppers in favor of drip compared to sprinkler irrigation with water of 4.4 dS/m, but there was no difference when non-saline water was used (Bernstein and Francios, 1973a).

The second advantage of drip irrigation lies in the pattern of salt accumulation under the point sources and the maintenance of high water content in the root zone by frequent but small water applications. High leaching is provided under the emitters where roots tend to proliferate providing the best conditions for optimum yield. In addition to salt leaching and accumulation at the wetting front (fig 11), salt tend to accumulate at the soil surface midway between emitters. This salt need to be leached before the next crop is planted, unless precision planting is possible by returning to the same rows as the previous row crop.

## Reclamation of salt effected soils

The only proven method of reclaiming saline soils is by leaching. Sodic soils require the addition of amendment or tillage to promote the leaching process. Leaching can be enhanced by growing very salt tolerant plants during the reclamation process. However, reclaiming saline soils by harvesting plants with salt they have taken up is not feasible. Adequate drainage and suitable disposal of the leaching water are absolute prerequisites for reclamation.

The amount of water required for the removal of salts from a saline soil depends on the initial level of salinity, soil physical characteristics, technique of applying water and soil water content. Leaching by continuous flooding is the fastest method but it requires larger quantities of water than leaching by sprinkler or by intermittent flooding. The latter, though slower, is more efficient and will require less water, particularly on fine textured soils, than ponding.

The relationship between the fraction of the initial salt concentration remaining in the soil profile, $c/c_o$, and the amount of water leaching through the profile ($d_L$) per unit depth of soil ($d_s$), when water is ponded continuously on the soil surface can be described by

$$(c/c_o)\ (d_L/d_s) = K$$

where K is a constant that differs with soil type. The above equation describes the curves in fig 12. For sandy loam soils K = 0.1 indicating that in order to remove 80% of the salt ($c/c_o = 0.2$) the soil pore volume has to be replaced once ($d_L/d_s = 0.5$), assuming a saturated water content of 50%. Fine textured soils (clay loam) will require three times as much water to remove an equal amount of salt (K = 0.3). The efficiency of leaching of clay soils can be considerably improved by intermittent ponding. Fig 13 shows that with intermittent flooding K for clay soils was reduced to 0.1 and that the three soils show the same pattern of leaching.

Reclamation by flooding may be relatively inefficient when tile or open drains are present as most of the water flow will take place through the soil near the drains, while midway between drains there will be far less leaching. The region between drains should be leached by basins separated from the region above the drains; or leaching should be done by sprinklers to improve efficiency (Luthin et al., 1969).

The reclamation of sodic soils usually requires the addition of chemical amendments to replace exchangeable sodium by calcium. Gypsum is the most common additive because of its low cost, good solubility and availability. The gypsum requirement (GR) to reclaim a sodic soil depends on the amount of exchangeable sodium ($Na_{ex}$) to be replaced by calcium (Ca). It can be calculated from (Keren and Miyamoto, 1990)

$$GR = 0.86\ d_s\rho_s(CEC)(Na_{exi} - Na_{exf})$$

Where $d_s$ is the depth of soil to be reclaimed (m); $\rho_b$ is the soil bulk density (Mg/m$^3$); CEC is the cation exchange capacity of the soil (mol/kg); $Na_{exi}$ and $Na_{exf}$ are the initial and desired final sodium fraction. According to this equation about 10 Mg/ha of gypsum will replace 30 mol/kg of Na to a depth of 0.3 m of a soil having bulk density of 1.32 Mg/m$^3$. Typically, 1 cm depth of water (100m$^3$/ha) will dissolve about 0.25 Mg of gypsum. Thus 4000 m$^3$/ha will be required to reclaim a soil of the above example to a depth of 30 cm.

It is difficult to reclaim a deep sodic soil profile in a single operation. The usual procedure is to partially reclaim the soil during the first year, then plant a shallow rooted crop and continue the reclamation process in the following years until the entire profile is reclaimed.

## Summary

Salinity and poor drainage are the most prevalent and widespread limitations to successful irrigated agriculture. This paper attempts to summarize our preset knowledge regarding the solution of some of the major problems.

1. For most crops on medium to fine textured soils an acceptable depth to the water table when salinity is not limiting, is about 85 cm.
2. Yield decline as water table level is lowered below 60 cm may be due mainly to lack of nitrogen. Between 60 and 10 cm depth the contribution of N deficiency to the total yields loss due to poor drainage decreases fro 10 to about 30%.
3. The bulk of evidence suggests that soil fertility, specifically N availability, does not change the level of tolerance of crops to salinity.
4. The bulk of evidence justifies the use of mean soil salinity within the root zone integrated over time as the representative value for estimating crop response. The most sensitive stage of growth is seedling development.
5. Temperature is the most critical among the environmental factors interacting with salinity. Plants are more sensitive at high than at low temperatures. High humidity tends to reduce somewhat the stress level.
6. When poor drainage results in salinization, salinity will further reduce crop yield. The degree of reduction depends on conditions and crop.
7. Crop water production function is not influenced by soil salinity. Crop evapotranspiration is reduced as salinity is increased thereby reducing crop water requirement.
8. The bulk of evidence indicates that there is no advantage in increasing irrigation frequency when salinity is present.
9. Drip irrigation is advantageous when salinity is present. Sprinkler irrigation with saline water may cause leaf burn on sensitive crops, which can be reduced by night irrigation.
10. Leaching of saline soils is more efficient using sprinklers or intermittent flooding.

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