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Cavazza L.

in

Bouchet R. (ed.).
Reuse of low quality water for irrigation

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 1

1989
pages 49-57

Irrigation systems and techniques for saline water

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In all regions that suffer, if only seasonally, from insufficient rainfall, agriculturalists have always sought to find additional water for irrigation. Today these efforts are increasing due to problems of increased population, the tendency toward more efficient labour and to higher standards of living. They are favoured by the availability of capital, progress in agricultural techniques, as well as by market expansion and organization. Under these conditions water at higher cost and of lower quality than was accepted in the past is now being used in dry areas, while in rainfed areas irrigation is also being extended to crops that traditionally have been considered in need of irrigation.

As a whole, in semi-arid conditions, the shift from dry farming to irrigation with brackish water has led to increases in yield and profit. These advantages, however, are lower the more saline the water is. This implies that the maximum level of water salinity actually tolerated in practical irrigation increases with aridity, management skill of the farmers and with market value of the product; it decreases with rising living standards.

For example, 15 years ago canning tomatoes irrigated with brackish water and hand harvested were an important crop in some areas of southern Italy in spite of the low yield. Most of the same water is now used for more valuable crops (mainly autumn-to-spring vegetable crops, or capsicum, eggplant, artichoke, grapes, etc.). It is possible that if the market becomes unfavourable for these valuable crops, the area irrigated with brackish water will contract and the highest acceptable salinity for practical irrigation will drop. This illustrates the evolving contrasts in the rush to extend the use of saline water in irrigation.

I - Leaching requirements

It is well known that the main problem in using saline water is to prevent the accumulation of excessive salt levels in the soil profile. One must establish an agricultural regime that ensures average soil salinity changes around a given acceptable stationary level. Irrigation management techniques have been empirically developed since ancient times in certain areas of the world, and for many decades scientists have been formulating rules that are still being improved. The classic "leaching requirement" concept is well known both in its first and second formulation.

The former equation (USRS Lab.; see Reeve *et al.*, 1967) is:

$L_R = E_{cw} / E_{cD} = S_w / S_D$,

where L_R = leaching requirement;

E_{cD} = electrical conductivity of water draining under the root zone;

E_{cw} = the same for irrigation water;

S_D and S_w = corresponding salinities expressed in soluble salt contents.

The second formulation (Bernstein, 1973) usually is:

$L_R = E_{cw} / (5\, E_{ce} - E_{cw})$,

but for drip irrigation it is:

$L_R = E_{cw} / 2.\, E_{ceM}$,

where E_{ce} = electrical conductivity of saturated soil paste and

E_{ceM} = Ece corresponding to 100% yield loss.

It is noteworthy that the second formulation relates water salinity to soil salinity for given leaching fraction. On the other hand, soil salinity might be related to relative yield of given crops (see Ayers, FAO, Irrig. and Drainage, Paper No. 29, 1976). In reality these equations imply a steady state irrigation without leaching from rainfall and are therefore more useful for desert conditions. Where drought is not so severe, as in semi-arid, sub-humid and humid regions, a more or less ample part of the salts accumulated during the irrigation season is leached out of the root zone by rainfall in the following season (mostly in winter in Mediterranean climates).

The theory of the leaching process in these latter conditions has not been sufficiently developed. The old leaching requirement formula, in terms of the salinity of drainage water, could take into account rainfall in a simple way:

$L_R = (E_{cr}.\, V_r + E_{cw}\, .V_w) / (V_r + V_w)\, .\, E_{cD}$
(Reeve *et al.*, 1967)

where $\underline{V}$ is depth (volume per unit area) and the subscript $\underline{r}$ refers to rain, and $\underline{w}$ to irrigation water; this is not the case with the new formula in terms of E_{ce}.

Available mathematical models for miscible liquid flow in the soil, although readily available, are still too cumbersome for routine applications in common farms and require the determination of too many detailed, non-routine parameters for the soil-plant system. As a result, they do not provide a simple and valuable substitute for practical use. One of the old very empirical criteria to this effect is that summarized in **Table 1** by Lunin *et al.*, 1960. In some cases, two winter rainy seasons are given the opportunity to leach out of the soil the salts from one irrigation season (Cavazza, 1968). Practical problems become more complicated when perennial crops, as well as some characteristics of the water source, are taken into account.

II - Irrigation methods

The suitability of different irrigation methods to the use of saline water is well known. Continuous flooding can be used for paddy fields as well as for soil desalinization when water is moderately saline. In contrast, discontinuous wild flooding from head ditches on poorly leveled land with fairly large streams of water results in large irregular patches of salinized soils (this method is now mostly disregarded). Basin, check and border systems are also not advisable when using saline water, particularly on low permeability soils. When the basin floor is corrugated, however, this method ensures a satisfactory salt leaching.

The versatility of furrow irrigation in these conditions has been recognized for many decades, especially in the adapted form of the ridge system (**Figure 1**). One can arrange the system so that the ridge is raised fairly high and the plants are placed in such a way that their crowns (e.g. lettuce) are just above the level of the water in the irrigation furrow, and the salt accumulates by capillary rise into the ridge above the rooting zone (Thorne, 1950).

In other cases, better results have been obtained by letting the salt accumulate on one edge of the ridge, while placing the plants on the central upper ridge surface where salinity is lower, or by sloping beds (see Ayers *et al.*, 1976); short furrows closed at the bottom, such as those customary in the Mediterranean region, ensure good salt leaching. Sub-irrigation might reduce excessive salt accumulation at the soil surface, provided the water table is sufficiently deep and moisture conditions are sufficient for seed germination and first stage growth of plants, i.e., by rainfall.

Overhead sprinkling is the worst method to apply saline water, due to the danger of leaf burn. For herbaceous crops, in the rare cases where possible, approaching the end of each sprinkling operation the plant could be turned from saline to fresh water to rinse the leaves. For trees, underhead sprinkling avoids such disadvantages. Sprinkling with adequate rain intensity provides for a satisfactory control of the depth of water application and of the leaching requirement. Pivot and Rainger sprinkling systems seem the least advisable for saline water, due to their usually small depth of single application.

Drip irrigation acts in axial vertical sections in a very similar way to what happens in vertical sections perpendicular to a furrow in the related system. Mathematical models for salt accumulation in soil and concentration in the soil-liquid phase under a dripper are well known (**Figure 2**; Bresler, 1975). With trees important asymmetries may arise due to the uptake activity of the root system. The most important feature of the application of saline water with this system is that salt tends to accumulate at the periphery of the wetted bulb in the soil and, near the soil surface, in the middle between plant rows, far from the root zone (Yaron *et al.*, 1973). For perennial row crops (e.g. artichokes, fruit trees) this a favourable condition, at least in desert areas, where natural rainfall is not likely to redistribute the salt in the root zone. For annual crops, a problem arises in that tillage operations mix up the soil and, anyway, it is not easy to replant a new crop exactly in the same unsalinized strips of soil.

III - Water sources and irrigation methods

In facing the problems of the choice of method for saline water application, the following cases should be considered:

a) continuous water availability from rivers at slightly fluctuating salinity;

b) saline water from wells in karstic or underdune aquifers;

c) and sewage water more or less treated.

In the first of these cases, most of the aforementioned considerations hold. Of main concern is the choice of a system which ensures satisfactory salt leaching, good germination (if the crop is annual) and no leaf burning.

When the water is pumped out of a well in karstic or underdune coastal aquifers, the situation might be somewhat more complex (Cavazza, 1968). A karstic aquifer consists of water contained in the network of cracks that are typical of the compact stratified calcareous formations of the Mesozoic. This crack system usually communicates with the sea and its statics and dynamics follow the theory of Ghyben-Hertzberg (Childs, 1969; Cavazza, 1981).

A certain part of the yearly rain water (i.e. two thirds) percolates through the shallow soil (1 m deep) that covers the mesozoic limestone and reaches through the cracks the underlying salt water of marine origine. The percolated fresh water, being lighter, floats on the saline water. On the bases of hydrostatic equilibrium, its upper fresh water table should exceed the sea level by a fraction of the thickness of the fresh water layer, equal to $\Delta h = (\rho_s - \rho_f)/\rho_f$ where ρ_f and ρ_s are the densities respectively of fresh and saline water. This fraction is theoretically about 1/40; in practice, however, due to the blurred distinction between saline and fresh water, $\Delta h = 1/30$ (Dabell, 1955; Cotechia, 1955; Zorzi and Reina, 1964).

The higher hydrostatic level of the fresh water table in respect to the sea causes the fresh water to flow toward the coast. On the other hand, the rainfall in some regions (e.g. in Mediterranean climates) is concentrated in winter, when a recharge of the karstic aquifer with fresh water occurs. From approximately March until September, on the contrary, the flow of fresh water to the sea prevails and the thickness of the fresh water layer gradually decreases (see **Figure 3**). If one draws up fresh water from this aquifer by a well, thereby locally lowering the water table, the floating balance of the fresh on the salt water is broken and the saline water will tend to rise to re-establish the aforesaid floating ratio of 1 to 30. It is obvious that the deeper the well reaches below sea level and the greater the pumping rates, and the thinner the fresh water floating lens, then the more easily the well will be invaded from below by the cone of salt water and the more salty its water will become.

Due to all these reasons the use of water from karstic aquifers in the Mediterranean region shows peculiar problems. First of all, its salinity is usually rather low (e.g. 1.5 to 2‰) at the beginning of the irrigation season (this is very favorable for the first stage of the crop cycle). During the season, however, the salinity gradually increases and very often is double at the end of September. Second, water salinity decreases and is more stable the farther the well is dug from the coastline. Third, water salinity can be kept relatively low only when the level depression in the well, hence the pumping rate, is small. The latter condition was once obtained by using animal-operated norias or water wheels as water lifting devices. Today, for wells near the coast line, low-discharge-rate pumps are used, coupled with drip irrigation systems or with accumulating farm reservoirs, when different methods are used (furrows or sprinklers).

Consider now the use of reclaimed municipal wastewater. Sanitary problems as well as cost problems are well known in this respect. The salinity of this type of water is often not too high; it might be higher when the sewage water comes from coastal towns, due to possible intrusion of sea water through failures in the sewage network. Technicians are inclined to strive for the cheapest solution in treating this type of water. When the process is limited to secondary treatment, and even more if to a primary one, the sprinkling of the water is the most hazardous system for health reasons; under-irrigation by water table control or by underground trickle irrigation seems to be preferable, at least theoretically.

Drip application of treated municipal wastewater is also used in such cases, despite the increased clogging hazard, so that pulse irrigation is preferable. When using drip irrigation the whole amount of water is delivered to small soil volumes, inside which the absorption of most of the suspended and dissolved matter can occur. This usually multiplies the effects of these materials on soil properties, both at the surface (decreasing water intake due to pore clogging or structure breakdown) and in the soil bulk (examples are shown in **Figure 4**). It is noteworthy, too, that common adjusted SAR determinations have to be revised for this type of water in order to take into account cation adsorption, mainly Ca and Mg, on the dispersed organic matter of the effluent (Sposito *et al.*, 1978; Acher *et al.*, 1981; Metzger *et al.*, 1983). Usually this implies a temporary increase of the effective adjusted SAR as compared to the computed one.

IV - Other technical aspects

Let us go back to the problem of preventing salt accumulation in the soil. The classic rule is to apply abundant watering depths (adequate L_R values) at not too long intervals, and to try to keep the soil hydraulic conductivity along the soil profile high. In reality, when there is a shallow, slowly flowing saline water table, and drainage is poor, or drains are too widely spaced, it is preferable to apply frequently smaller water depths, in order to reduce the temporary rise of the water table into the root zone.

In karstic areas, soils are usually rich in iron and aluminium sesquioxides (mainly alfisols), so their structure is rather stable and ensures good permeability. The irrigation with saline groundwater is applied chiefly to vegetable crops and grapes. The traditional strategy of irrigating the same soil every other year, so as to ensure a satisfactory leaching of salts from the soil, was once met by suitable rotation, e.g., tomato (irrigated) – cabbage (transplanted in July in rows between those of tomato and irrigated in the first stage) – wheat (or oats or barley; no cropping the next summer). Only with water salinity less than 2‰ in the spring is it possible to irrigate each summer; this is necessary for perennials such as artichokes or grapes. The depth of water for each application (through furrows) is usually small (about 250 m^3/ha) and the average frequency about one watering every six to seven days (three to four days at peak of dry season), reaching a total seasonal water depth of 3,000-4,500 m^3/ha. With this technique, given the prevailing potential evapotranspiration and the hydrological properties of the soil, its moisture is usually kept very near or somewhat higher than field capacity so that a continuous slow drainage of saline water is ensured under the root zone.

The problem becomes more intriguing when grapes need to be irrigated. Contrary to common theoretical assumptions, for this crop it is not beneficial to satisfy the whole water demand, as it is expressed by its maximum evapotranspiration (ETM = ETc - ETo $\times$ K), because an excessive foliage development and fruit enlargement corresponds to a low quality product (low sugar content, delayed maturation, poor storage and shipping capacity). Usually only about 2/3 of the whole ETM is considered satisfactory under this aspect. This implies, however, that the frequency of irrigation is much reduced (i.e. two and four applications per season preferably at given stages); more severe water stress is permitted while only limited leaching is still maintained. In very dry years, the salinity of the karstic ground water increases (both for shallower fresh groundwater layer and for greater average pumping rate), especially toward the end of the dry season, and the problem is to choose between a stronger plant stress caused by water shortage or one caused by higher soil salinity. In very dry years, plants can die before autumn rainfall comes to help. No satisfactory criteria are now available to optimize the irrigation technique under these conditions. Similar situations might occur also when saline water is stored in reservoirs; in hot, very dry seasons, water salinity can increase by evaporation to a point where its use with customary techniques becomes questionable.

In some cases, besides the disposal of a non-limiting amount of saline water for irrigation, a constant, limited flow of fresh water is also available. The problem arises in choosing between the use of saline water for tolerant crops and fresh water for sensitive ones, or the mixing in part or as a whole of fresh and saline water to irrigate all crops. The problem has to be solved for single cases by taking into account as functions or independent variables:

a) yield of each crop as a function of both water salinity and leaching fraction;

b) available fresh water flow;

c) cost of both saline and fresh water per unit volume;

d) cropping expenses other than those for water application, for each crop and per unit area of irrigated land, and

e) market price for each crop.

The functions (a) are usually simplified in such a way as to be represented by horizontal segments (y = const.) in a domain from zero to a given threshold and then to a sloping line from this threshold onward. Three parameters are then required for each crop; linear programming techniques are suitable.

Broadly speaking, in situations where the water demand per unit area is large, the stronger the difference between these thresholds for two crops, the steeper the line for the sensitive crop and the lower the slope of the line for the tolerant crop, the higher the product of market price by maximum yield for the former crop compared to the latter one, the higher the cost of fresh water compared to application of the saline one, the lower the cropping costs of the sensitive crop compared to the tolerant one, and the lower the relative available volume of fresh water, then the more convenient is the use of fresh water for the sensitive crop and the saline water for the tolerant one, without any mixing. Social, historical and economical aspects should also be taken into account.

In some situations a very pronounced peak for water demand occurs only in a short period (e.g. in July, under Mediterranean conditions), while appreciable rainfall is available in the earlier growth stages of the crop. At this time the irrigation requirement is low and it is then suitable to apply only fresh water in these earlier stages, when the amount of such a type of water meets the irrigation requirements while the crops are mostly in a more sensitive stage to salt. One could shift later on to mixed or saline water. This condition is naturally actuated when exploiting karstic aquifers that show increasing groundwater salinity over the irrigation season.

When fresh water is stored in a reservoir, the problem has to be put in a somewhat different way. In this case the given is not the flow rate of available fresh water but the total volume of this water in the irrigation season. The solutions of the problem involve some delay in the use of fresh water, reducing it in the intermediate stages, while permitting more balanced water salinity in the peak period. When the water is applied by sprinklers, the possibility of shifting at will from saline (or mixed) to fresh water favours overhead sprinkling (short final rinsing of the canopy with fresh water).

In solving all these problems one should be aware of the effects, both positive and negative, of irrigation with saline water on product quality and take them into account when assessing their market prices. It has been found that salinity conditions might increase the number of fruits per plant, while reducing the average fruit weight (Cavazza, 1968). Fruits are thus usually smaller but more tasty, have better colour and consistency, are richer in mineral salts, especially sodium chloride, and sugar, have higher dry residue and are more resistant to storage and shipping (Pantanelli, 1937). Some other widely held beliefs on this subject should be properly tested, i.e. that saline irrigation makes eggplant fruits more bitter and fibrous, pepper hotter, cucumber more bitter, or that crucifer plants tend to blossom earlier and broadbean becomes more resistant to Orobranche.

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Table 1: Permissible number of irrigations with brackish water between leaching rains for crops of different salt tolerance

Irrigation water		Irrigations for crops having		
Total salts	Electrical conductivity	Good salt tolerance	Moderate salt tolerance	Poor salt tolerance
Parts per million	MilliSiemens/ centimeter at 25° C	Number	Number	Number
640	1	-	15	7
1,280	2	11	7	4
1,920	3	7	5	2
2,560	4	5	3	2
3,200	5	4	2-3	1
3,840	6	3	2	1
4,480	7	2-3	1-2	-
5,120	8	2	1	-

Source: Lunin et al., 1960

Figure 1: Patterns of salt accumulation in soils irrigated by furrows. Dotted areas = salt accumulation (from Bernstein *et al.*, 1957; and Ayers *et al.*, 1976

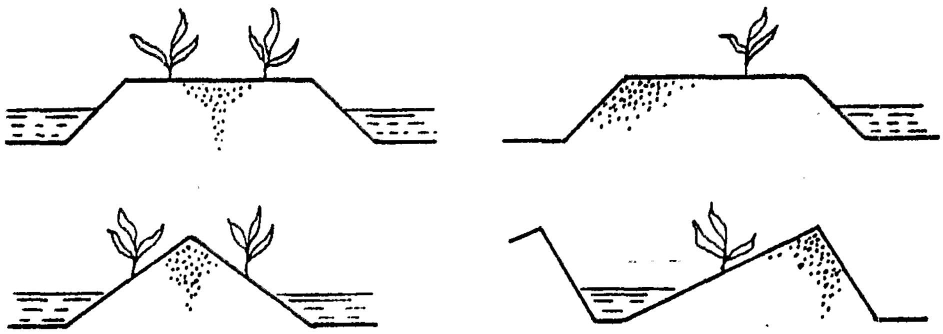

Figure 2: Salt distribution in soils under drip irrigation. Left: sandy soil; right: loam. For each graph: left half: salt concentration in the soil solution (% of increase over the concentration of the irrigation water); right half: salt content in the soil (meq/dm3 of bulk soil volume). From Bresler, 1975.

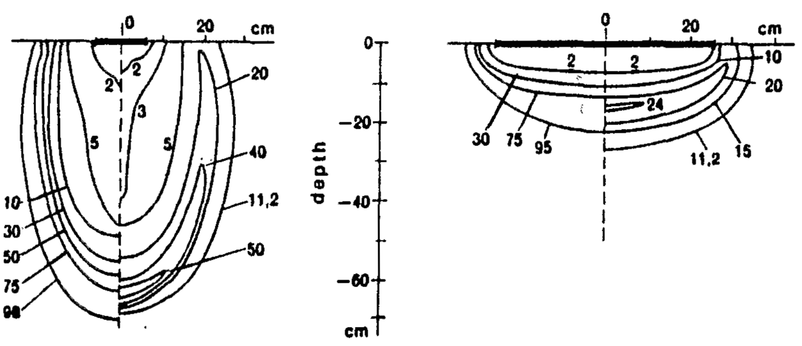

Figure 3: Pattern of fresh water distribution in a karstic acquifer, floating on saline water and gradually flowing to the sea. Left: thinning of the fresh water lens over the dry season. Right: rising of saline water cone and danger of well salinization caused by high rate pumping

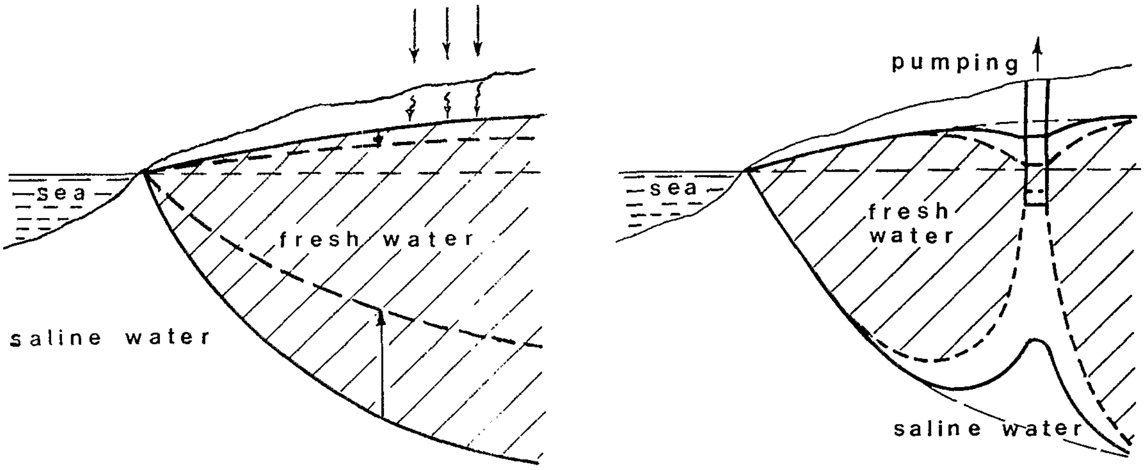

Figure 4: Accumulation in time of Na and Mg under the drippers, after irrigation with secondary affluent from municipal sewage water. Differences against non irrigated control; partial winter leaching is also evident
(?: unpublished data from Idroser)