Chapter 1

Irrigation and Drainage in Agriculture: A Salinity and Environmental Perspective

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Additional information is available at the end of the chapter

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Abstract

Whereas irrigation and drainage are intended to address the shortage and surplus of soil water, respectively, an important aspect to address is also the management of salinity. Plants have a limited tolerance for soil water salinity, and despite significant gaps in our practical knowledge, an impression of acceptable salinities is available for many crops. To manage soil salinity, the Leaching Requirement is an old, yet useful, concept. In this chapter, we extend this concept for soils with shallow groundwater. Particularly if shallow groundwater is saline, management is needed to avoid capillary rise of this water into the root zone. One of the tools to do so is Climate Adaptive Drainage (CAD), for which many practical gaps in knowledge remain. Also, soil mulching, of which a special case is considered in more detail, i.e., using plastic covers, may be beneficial for many purposes, including improving the water and salt balances of the root zone. However, use of plastics may have significant adverse effects. Due to water shortage, also wastewater may be re-used for irrigation. For this reason, the hazard of sodicity due to elevated Na concentrations in domestic wastewater is highlighted.

Keywords: salinity tolerance, Leaching Requirement, groundwater, adaptive drainage, soil mulching, plastic mulching, wastewater re-use, sodicity, modelling

1. Introduction

Although arid and semi-arid regions have a potential for yielding multiple crops per year, due to the large incoming radiation, this potential is profoundly limited by the small annual rainfall. An impression of the distribution of dry areas is shown in **Figure 1**, which is based on the aridity index (AI), defined as annual precipitation divided by potential evapotranspiration.

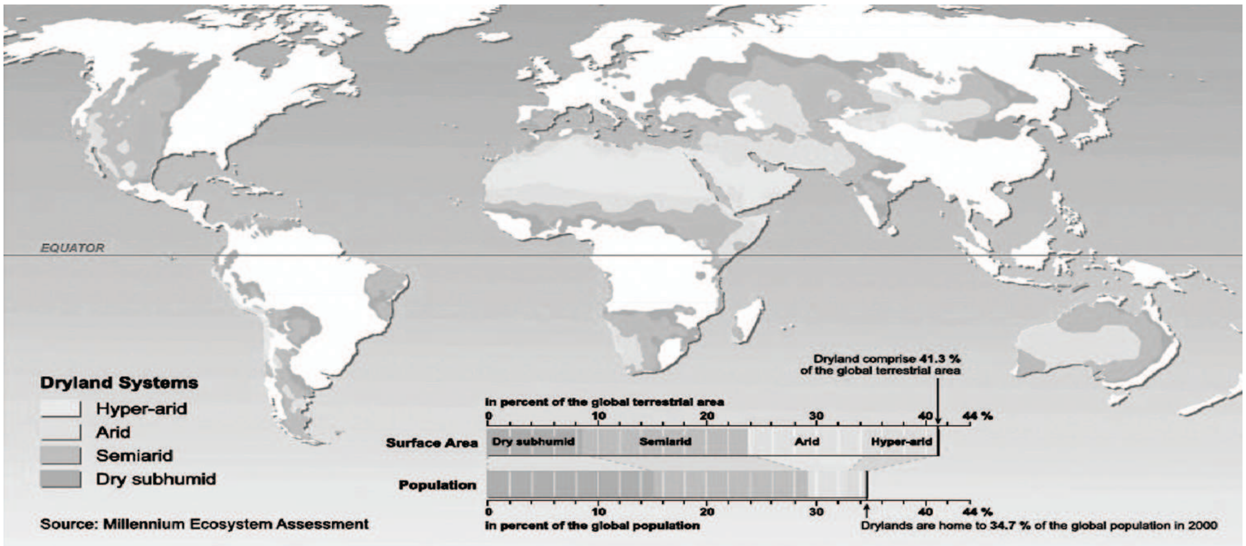

Figure 1. Distribution of dryland regions (from: Millenium Ecosystem Assessment, Chapter 22, 2005).

$$AI = P/ET_p \tag{1}$$

where P is annual rainfall and ET_p is potential evapotranspiration (both mm/y). Therefore, **Figure 1** shows the main regions, where an additional supply of water, besides rainfall, is needed or even crucial for agricultural production. However, also in the regions where water supply is sufficient, seasonal drought can be a farmer's risk. This is the case in a humid temperate country as the Netherlands.

Insufficient rain falls have to be compensated for, to ascertain sufficient agricultural yields. Irrigation using good-quality river water, groundwater and, sometimes, wastewater has been used for ages. Irrigation is often accompanied by drainage, which is the natural or artificial removal of surface and sub-surface water from a given area. Artificial drainage is always needed, except in cases with deep groundwater levels. In most river delta regions, drainage is a must to avoid water logging. This is not the only reason, because avoiding salinization is a recognized aim of drainage, as is illustrated in this chapter.

Research on irrigation and drainage has been considerable and this is not surprising as irrigated agriculture has been practiced during the past 5000 years, e.g,. in Mesopotamia. Due to long-term changes, water availability for irrigation could decline or salinity problems could develop. The underlying cause for agricultural yield depressions upon salinization is that most terrestrial plants tolerate only a limited salinity of soil water. The term salinity is usually associated with concentrations of sodium chloride (NaCl), but may be interpreted more broadly as the presence of ions in water. Rainfall usually contains few ions, but agricultural fields are often irrigated with groundwater or surface water, where this is different. The salts that may give problems in agriculture may be derived from different sources: (i) water in contact with soil material induces physical and chemical weathering, which is associated with release of ions, of which the concentrations may be increased due to evapotranspiration; (ii) groundwater may be brackish or saline due to different geohydrological causes such as sea

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water intrusion and the presence of old marine sediments; and (iii) use of river water with some level of salinity, originating from groundwater, sea, or industry. Salinity is often expressed as concentration (mass per volume of water), electrical conductivity (EC), or total dissolved solids (TDS).

The scope of this chapter is to address a number of environment-related aspects such as salinity and recent developments that may develop into contamination problems. Our motivation is that simple ways to predict developing environmental contamination are quite limited and sometimes not even recognized. After some background information on the vulnerability of plants for salinity, guidelines are provided for anticipating the salinity levels that may be expected in the root zone, which do not require complicated models. Some other general environmental hazards associated with irrigated agriculture are identified, as related with plastic mulching and re-use of wastewater in agriculture.

2. Salt tolerance of plant species

Efforts to limit the salinity of the root zone are, at the end, aimed at limiting adverse impacts of salinity on primary productivity of crops. In a somewhat broader sense, growth of both crops and botanic species, product quality, and other measures related to plant well-being are important in the assessment of salt-induced adverse effects.

Plants exposed to elevated salinity may experience different forms of stress. Due to the high osmotic value of saline solutions, soil water may become less available for plants to accommodate their transpiration, which directly affects primary production [1, 2] in a similar way as drought. However, it is also well known that salts (e.g. involving Na^+, Cl^-) may be toxic for plants or that toxic components such as boron (B) and selenium (Se) become better bioavailable under saline conditions. For boron, the concentrations that separate deficiency and toxicity are close together [3], making an optimum availability difficult to accomplish. In addition, induced nutrient deficiency has been well documented, e.g. for iron and nitrate [4, 5]. In many dose-effect types of exposure studies of salinity, permanent stress is considered. However, in many field situations, salt stress occurs only in limited periods or one season. Typically in temperate conditions saline stress is periodic, e.g. due to tidal or seasonal fluctuations, and is followed by salt leaching conditions. However, research on salt stress duration and plant response is quite limited.

Salt tolerance has been investigated much for agricultural crops, both in field and greenhouse conditions and, particularly, for the case where salts enter the root zone. Different plant species have different salt tolerance and strategies to deal with salinity [6, 7]. It has been well established that also different genotypes of the same species may differ according to their salt tolerance ability [8]. The accumulated experimental evidence of salt tolerance functions (MH) for crops has been summarized [2], which describe the salt concentration range in the root zone where transpiration (hence primary production) is unaffected, and in the larger salt concentrations where transpiration is reduced. Since 1977, such 'MH'-functions have been adjusted and developed for other crops or for different environmental conditions [9].

MH-functions make it is possible to compare different plant species with regard to their vulnerability to salinity.

The MH-functions describe how soil or soil water salt concentrations affect primary production. They seem to differ for different soil types and climate and weather conditions. MH-functions, apart for comparing species for salt vulnerability, are also important for predicting crop yields, because most modelling uses the MH-concept [10–13]. The aim of such modelling is often to really predict yields, e.g. if climate changes, or to generalize experimental observations to other soils or geohydrological situations. MH-functions are often used to measure water availability and salinity of the root zone throughout the growing season, which are relatively constant. However, in the field, this is generally not the case. Particularly for distributed modelling, additional assumptions on how plants spatiotemporally deal with variability are needed [14]. For instance, plant roots may compensate for dry or saline layers in soil by taking up water from other layers, but do they do so based on the water content, water potential, or a mixture of these properties? At the moment, the experimental evidence is predominantly based on water contents and salt concentrations that are as homogeneous as possible. Compensation strategies may differ according to plant species or even genotype.

In agricultural modelling, emphasis has been on salinity effects on the osmotic potential of soil water and its availability for plants. Ion specific effects as toxicity or induced deficiency are important, but generally disregarded in modelling. The reason is that crops are often well fertilized, but also that for modelling ion-specific effects, a multicomponent approach is needed as in HP2, UNSATCHEM, and SWAP-ORCHESTRA [15]. Not only is multicomponent modelling much more demanding with regard to parameterization, data, and computational efforts, but also data are needed for different plant species. This is not a trivial effort.

As much as crops have been investigated for salt tolerance, this not the case for landscape/decorative plants. Native vegetation has been investigated much from the perspective of plant ecology [16] or mapping [17]. Spatiotemporal variability of abiotic factors is often ignored, although salt tolerance of species and systems is estimated by investigating their spatial distribution and plant traits. Out of thousands of papers, only about 50 dealt with deciduous trees [18, 19]. Nevertheless, also for these categories of plants lists have been produced for their salt tolerance [20, 21]. In some cases, such listings give a quantitative grading, but a relative classification may be more appropriate [22] because the experimental techniques, quality of data, and used metrics to describe the damage may differ profoundly among papers. In view of the limited data for non-crop plants, at this moment modelling of climate change on the distribution of botanic species may be hard or impossible.

An important salt exposure pathway is that of salt spray and sprinkler irrigation. Although the importance of exposure of the leaves has been demonstrated [21, 23–25], this pathway is generally ignored in modelling. Mostly, it is mentioned that uptake of salts (notably Na and Cl) by the leaves and toxicity lead to necrosis, but osmotic effects are seldom mentioned. Timing of sprinkling plays a role, because sprinkling at night, or at frequencies that limit the duration that leaves are wet, appear to affect the degree of adverse effects: the impact is smaller as leaves are wet shorter, or transpiration is smaller. The direct (leaf exposure) pathway was also recognized [26] to enhance the impact of exposure through the root zone.

Browsing through the literature, it is clear that salt effects depend on plant species, genotype, salt composition, soil type, climate and weather conditions, and geohydrology. These factors all modify the plant's response to salinity, but some are ignored completely (ion specific effects; leaf exposure) in crop and soil models. The large complexity and significant gaps reveal that data can be fitted and described by models, but true prediction may be feasible only for broad features and large uncertainty bands.

3. Irrigation and salinity

All sources of soil water, except for artificially desalinated (deionized) water, have one thing in common: they all contain dissolved salts (together with non-ionic compounds dissolved compounds are comprehensively called solutes) to some degree. In case of rain water, little salt is dissolved but in case of brackish or saline water, salt may be present in such quantities, that the density of the liquid is increased. Thus, sea water contains 35 g/l of salt (mainly NaCl) and has a density of 1.025 g/l or 1025 kg/m^3. These density differences may have a significant effect on water flow, as will be considered later in this chapter. Groundwater and river water often contain solutes that originate from the geological formations that the water has flown through, as well as from biological or human activities. These ions include calcium (Ca^{2+}), magnesium (Mg^{2+}), carbonates (HCO_3^-), sulphates (SO_4^{2-}), nitrates (NO_3^-) and phosphates (PO_4^{3-}).

When water evaporates from the soil or is transpired by plants, most salts are left behind in the soil. Therefore, it is necessary to be alert for the hazard that too large quantities accumulate in the soil solution. This understanding was communicated already in the first half of the previous century, and described in the famous Handbook 60 [27]. For illustrative purposes, the Leaching Requirement (LR) is of use. It is based on annual water and salt balances for the root zone or 'plough layer' (here the term root zone is used). In words, both balances tell how large the (water or salt) accumulation rate is in dependence of the inflow of irrigation and rainfall water and the outflow of drained water. On the longer (multi annual) term, the water balance is zero, i.e., the net water accumulation or depletion is zero. If this were not the case, the soil would become completely water saturated, or water deficient (note: at the scale of one or several years, the water balance may be positive or negative, but on the long run, this cannot be the case as otherwise we deal with an inundated soil or completely dry one). Hence,

$$D_{iw} = D_{ET} + D_{dw} \tag{2}$$

where D stands for a 'depth of water layer', as related to a flux through a designated area (in m^3 m^{-2}y^{-1} or in mm y^{-1}), *iw* stands for irrigation water, *ET* for evapotranspiration, and *dw* for drained water. For the salt balance, it is illogical that the balance is zero: salts may accumulate or be depleted until no salt is present. Accordingly, the salt balance would be

$$\frac{\Delta\theta C z_r}{\Delta t} = D_{iw}C_{iw} - D_{ET}C_{ET} - D_{dw}C_{dw} \tag{3}$$

where θ is the volumetric water fraction, C the salt concentration, z_r the root zone thickness, and t is time.

Usually, water taken up by plants for evapotranspiration contains some salts (and nutrients), but far less than in irrigation water for those cases where salinity is an issue. Therefore, the term for ET can be neglected and Eq. (3) can be modelled for if more salt is coming in than is in equilibrium with initially present salt. The salt concentration increases, giving a behaviour as is shown in **Figure 2**.

As **Figure 2** reveals, short term variability can lead to an erratic pattern of root zone salinity. Although this variability may be important, for instance if it is a seasonal pattern, particularly the long term level at which salinity stabilizes is of main interest in a sustainability assessment: will the adopted management (involving how much is irrigated, how much is leached, in view of the quality of irrigation water) lead to unacceptable salinization or not?

On the long term, the salinity acquires the level of the dashed line in **Figure 2** and does not change anymore: the term to the left of the =– sign of Eq. (3) becomes zero. Then, Eq. (3) can be recast as follows:

$$D_{iw}C_{iw} = D_{dw}C_{dw} \tag{4}$$

where we remember that $D_{iw} = D_{ET} + D_{dw}$.

Already in Handbook 60 [27], it was realized, that the concentration in water that drains out of the root zone is equal to the concentration in the root zone, if this zone is at field capacity. Hence, $C_{dw} = C_{soil,FC}$. Inserting this in Eq. (4) and re-arranging leads to

$$\frac{D_{iw}}{D_{dw}} = \frac{C_{soil,FC}}{C_{iw}} \tag{5}$$

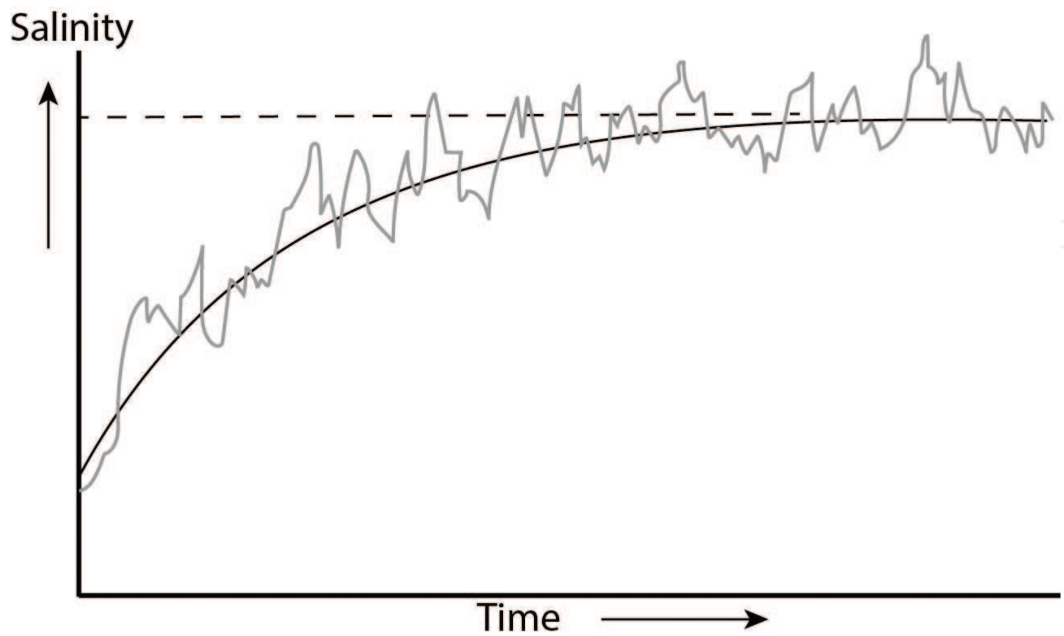

Figure 2. Increase of salinity ($\theta C z_r$) of a root zone according to Eq. (3) for short term fluctuations of water or salt concentration (grey line) or constant irrigation water concentrations and rainfall, ET and drainage rates (black line).

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For illustration, this is a very useful result. Usually, the quality of irrigation water (here represented by its salt concentration) is known, as it is easily measured. Then, it is easy to determine with Eq. (5) how much irrigation water must be applied (in view of the amount of evapotranspiration, represented by $D_{ET} = D_{iw} - D_{dw}$) to drain enough to keep the soil salinity ($C_{soil,FC}$) below the level that a certain crop demands.

Practically convincing is it, to show what happens if one does not drain at all. In that case, $D_{dw} = 0$, and the division by zero implies that $C_{soil,FC}$ becomes infinitely large. The compelling message of this simple illustration is:

1. If regular leaching of salts out of the root zone does not occur, salinity will increase unbounded: concentrations continue to increase.

2. This increase of salinity may take time, particularly if irrigation water is of good quality, but it is still inevitable. On the long term, salinity must increase if salts are not leached, and agricultural soil will become too saline for agriculture, as old civilizations in Mesopotamia testify [28]!

3. Really unlimited increase of the concentration will not occur, of course, in reality. This is due to chemical precipitation of salts as soon as the solubility product is exceeded. Where this solubility product is salt as well as environment dependent, it defines an upper limit to salt concentrations in solution. The environment dependency is related with e.g. temperature, but also the solution composition. For instance, gypsum is known to be better soluble under saline (or more general: higher electrolyte concentration) than low salt conditions.

4. Impact of groundwater

To determine the need for leaching salts without consideration of groundwater is often inappropriate. In many regions, and particularly in lowlands as coastal plains and delta areas, groundwater is shallow. For the salt-affected Hortobágy area of Hungary, the guideline was developed, that if groundwater is shallower than say 3 m below the soil surface, the upward capillary flux may be significant enough to be important for the water and salt balances [29]. Simulations support this guideline [30].

The relationship of the impacts on the root zone wetness between natural precipitation (mostly rainfall) and groundwater (capillary rise) can be complex. Whereas rainfall is an independent forcing, capillary rise of water depends on the root zone water content pressure, soil hydraulic properties, and groundwater depth: root zone water affects capillary rise and is affected by it. The same is true for infiltration and runoff [31]. The complexity was one of the reasons of a new school of Ecohydrology to analyze low-dimensional flow models [11].

In the simplest form, that approach of modelling considers a root zone of which the volumetric water fraction θ depends on infiltration, evapotranspiration, and drainage. At the same time, θ is the variable that determines these fluxes (plus runoff). Vervoort and Van Der Zee [32] extended such models with capillary rise of ground water. These water balance models represent the layer between root zone and groundwater level with a functional dependency of θ and these fluxes.

The impact of seasonality on the water dynamics can be profound, and many countries are characterized with seasonality. This is also the case for root zone salinity, because dissolved salts (of alkali and earth alkali cations) respond quickly on the water fluxes. For this reason, the salt concentration of the root zone often shows a distinct short term fluctuation as in **Figure 2**. Using the ecohydrological framework with minimalist (parsimonious) models [11, 32], salt accumulation was investigated [12]. The latter took capillary rise of brackish groundwater into account. Their root zone water balance, was therefore given by

$$\varphi Z_r \frac{ds}{dt} = P - R(s) - ET(s) + U(s) - L(s) \tag{6}$$

where φ is porosity, Z_r is root zone thickness, s is water saturation (about equal to θ/φ), t is time, P is rainfall or precipitation rate, R is runoff rate, ET is evapotranspiration rate, U is capillary upward flow rate, and L is leaching or drainage rate.

The complexity of Eq. (6) is that the rainfall is erratic: rain occurs with irregular intervals and each shower has a different intensity and duration. Therefore, water saturation s and salt concentration c vary irregularly with time.

The salt mass balance is given by

$$\frac{dM}{dt} = \varphi Z_r \frac{dsC}{dt} = U(s).C_Z - L(s)C \tag{7}$$

with M the total mass of salt, C_Z is the salt concentration in the groundwater (fixed) and C is the salt concentration in the root zone. In Eq. (7), it is assumed that the other water fluxes (P, R, ET) do not transport appreciable quantities of salt, which is often reasonable. Solving Eqs. (6) and (7) shows patterns similar as **Figure 2**. If saline soil is washed with good-quality water, the mean concentration decreases but short term variability still occurs. If seasonality is profound, intra-annual periods of drought will often coincide with periods of root zone salinity, both having a tendency to reduce crop yields.

Taking into account the often erratic variability of weather [33], recently the salt accumulation in the root zone was investigated, considering that root zone salinity levels respond fast to the water quality of incoming fluxes (rainfall, irrigation, capillary rise). In general, say in 10 years, the root zone concentration attains a dynamic equilibrium with rain, irrigation water, and groundwater quality.

For water managers, it is important to be able to assess whether intended water and salt management is sustainable on the longer term: will the use of irrigation water with a known salinity lead to too much salinity? And if it does, to what degree: will crops that are planned to be part of the rotation scheme show reduced yield? If for such questions only the longer term level of the concentration in the root zone is important (i.e., the plateau in **Figure 2**), a simpler assessment may be sufficient, than analyzing Eqs. (6) and (7).

Comparing simulated salt concentrations using a root zone model [12], and analytical approximations as Eq. (8) that are as simple as the Leaching Requirement approach, a good agreement was obtained, as shown in **Figure 3**, with ratios close to one. Apparently, the longer term mean concentration levels can be quantified well if short term variability of weather is ignored using

$$\langle C \rangle = \frac{\langle D_{cr} \rangle C_Z + \langle D_{irr} \rangle C_{irr}}{\langle D_{dw} \rangle} \tag{8}$$

where brackets <.> refer to time averaging, subscripts *cr*, *Z*, *irr*, and *dw* stand for capillary rise, groundwater level, irrigation water, and drainage water, and D is the respective flux in mm or m water layer for the averaging time (usually one year, so D in mm/y). Eq. (8) holds if both groundwater (concentration C_Z) and irrigation water (concentration C_{irr}) carry significant salt quantities, and implies that the mean soil concentration, and the mean leaching concentration, is given by a weighted average concentration of the water fluxes.

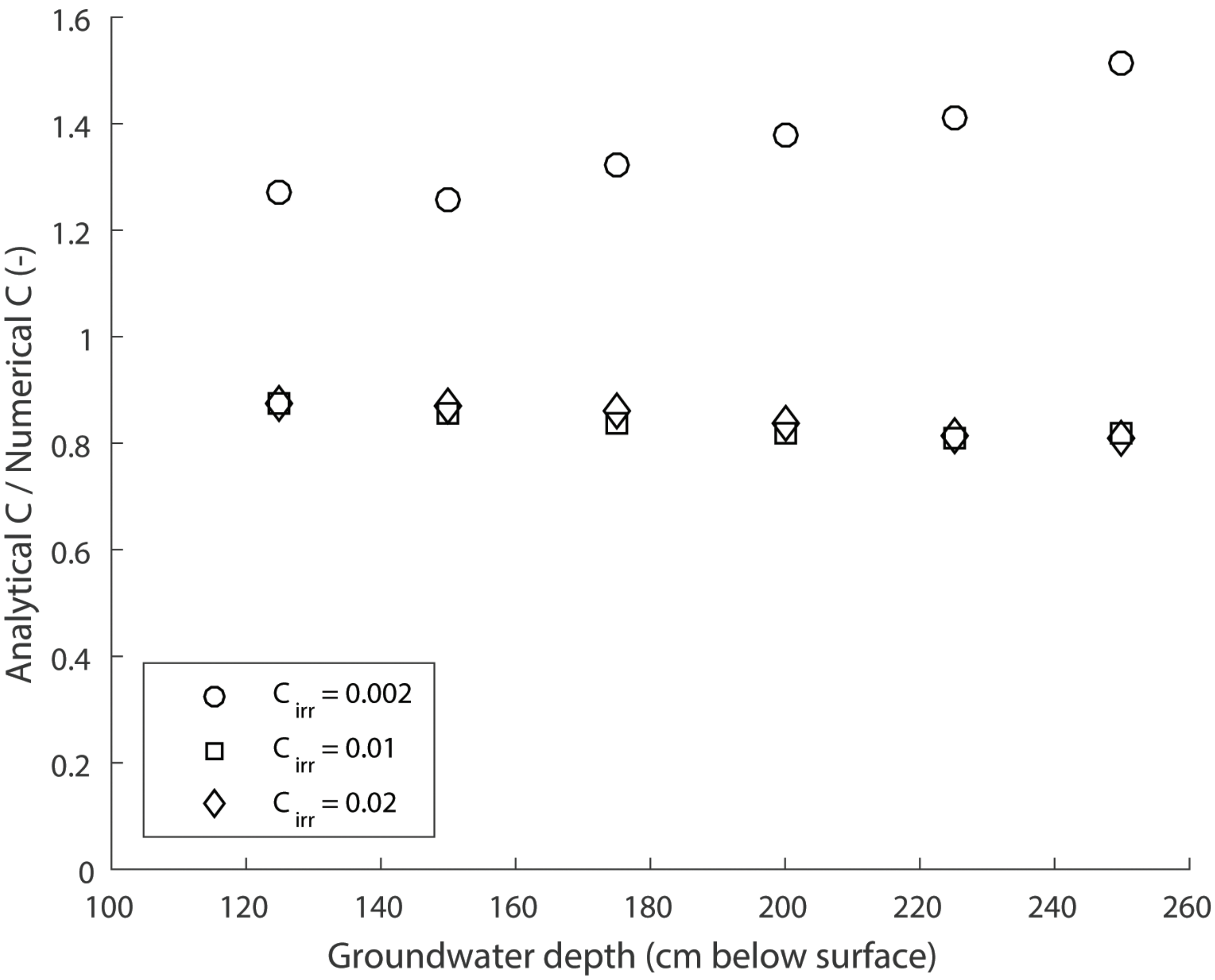

Figure 3. Ratio of calculated root zone salt concentrations with Eq. (8) and as modelled numerically, as a function of groundwater level (Z_f in cm below surface) for a temperate climate as in The Netherlands. Irrigation water salinity given by C_{irr} in mol l^{-1}, and groundwater salt concentration of 0.02 mol l^{-1}. Adapted with permission from Ref. [33].

Irrigation can be modelled similar as rainfall, except that it is a managed source of water (timing is a managing decision) and that it may contain more dissolved salts than is common for rainwater. To predict salinization using simple means, for cases not considered by the Leaching Requirement (e.g. if capillary rise is important, and possibly it contains appreciable dissolved salts, if both rain water and irrigation water infiltrate, with different salinities) is useful and Eq. (8) is an example of such a simple management tool.

With numerical models and with approximations as LR and Eq. (8), a judgement can be made whether root zone salinity is expected to become too high under the current practice, and how much and how good quality irrigation water will be needed to limit salinity to desirable levels. These tools, however, are generic and for a good desalinization of soil, the local conditions need to be known well. Besides the management decision to install a drainage system, various measures can be taken to homogenize fields (e.g. surface level) and improve the efficiency of salt leaching. Tools as discussed in this chapter may fine-tune the leached salt concentrations to agree with the farmer's needs and the salinity in discharged drainage water that are acceptable downstream.

In most model approximations for the long-term salinity of the root zone, it is assumed that level and quality of groundwater are unaffected by the root zone water and salt balance. This is a simplification. Root zone drainage water may affect groundwater, and cause fresh water bodies to develop in coastal dunes [34]. The thickness of the freshwater bodies floating on top of saline water as follows from Archimedes' law. Various approximations have been developed since the nineteenth century for the thickness of fresh water lenses, assuming a sharp interface between fresh and saline water and different assumptions on the outflow at the edge of the lens and movement of the saline water [35] (**Figure 4**).

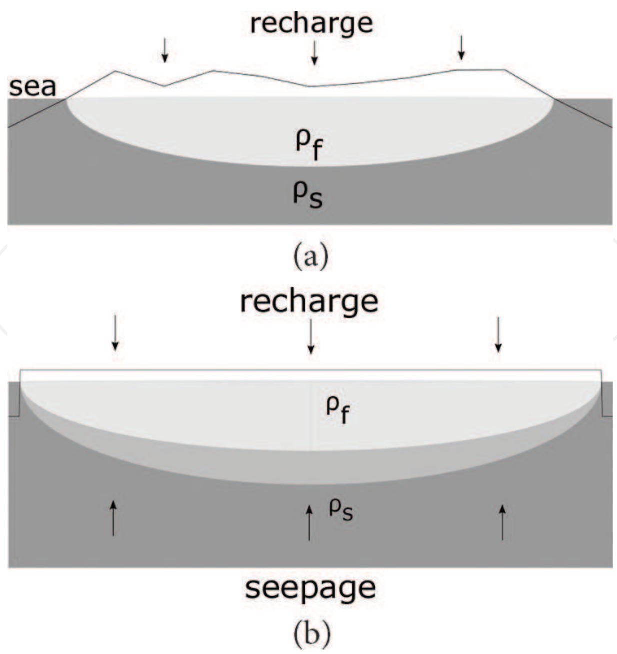

Figure 4. The freshwater lens (a) in a dune (the classical Ghyben-Herzberg lens) and (b) in an agricultural lowland field as considered by Refs. [35, 36].

Mostly, fresh water lenses outside the dune areas have been studied for situations where the soil surface is close to the sea level, and open water is at or even below this level. Then, groundwater seeps upward into the open water, and thin fresh water lenses form, that may respond quickly to changes in rainfall and evapotranspiration. They are found not only in coastal regions [36], but also in central Australia due to incidental flooding, to form an important source of fresh water to indigenous vegetation [37, 38] and 'inland' parts of PR China.

Because small fresh water lenses are vulnerable to disappear during extended periods of drought, Stofberg et al. [33] assessed how this vulnerability depends on a number of conditions. To avoid this depletion of fresh water, active management of water storage in wet periods is needed and one of the tools may be Climate Adaptive Drainage (CAD).

5. Drainage dimensioning and advanced options

Drainage of water is needed to avoid water logging, poor mechanical behaviour, and increasing salinity. This recognition has made drainage technology as well as theory to become topics of high importance in soil, water, and agricultural science. Due to the good economic situation, high population density, and usually shallow groundwater table, drainage has particularly been investigated in detail in The Netherlands. Basic theory has been developed by, e.g. Hooghoudt and others.

Dimensioning of drainage for (often flat) fields in agricultural use, is commonly aimed at management of groundwater levels to avoid water logging, poor tractability, structure degradation due to grazing cattle, and water saturated and anaerobic conditions. In their simplest form, the steady state water level between two ditches or drains can be obtained from the combination of Darcy's law and the water balance, with the Dupuit assumption. For a steady-state rainfall rate of P, we obtain

$$P = q = \frac{4K\left(H^2 - D^2\right)}{L^2} \tag{9}$$

where P is recharge (net infiltration) rate (m/day), q is the discharge into the drain or ditch (m/day), K is the hydraulic conductivity of soil (m/day), H is the water level halfway two drains measured from the impervious basis of the phreatic aquifer (m), D is the drain level measured from the same basis (m), and L is drain spacing (m). With Eq. (9), it is possible to determine the spacing needed to limit D to a value sufficiently below the soil surface.

As was already mentioned, in many climate zones it may be important to save water, for instance because precipitation may occur in a season that is unfavourable for crop production, and primary production in general. One of the tools to enable temporary storage is Climate Adaptive Drainage (CAD). In CAD, the level of drainage can be dynamically varied to improve flexibility with regard to water stored in the soil profile. The basis of this technique is quite simple: drainage, e.g. using tile drains, is no longer passive but active by

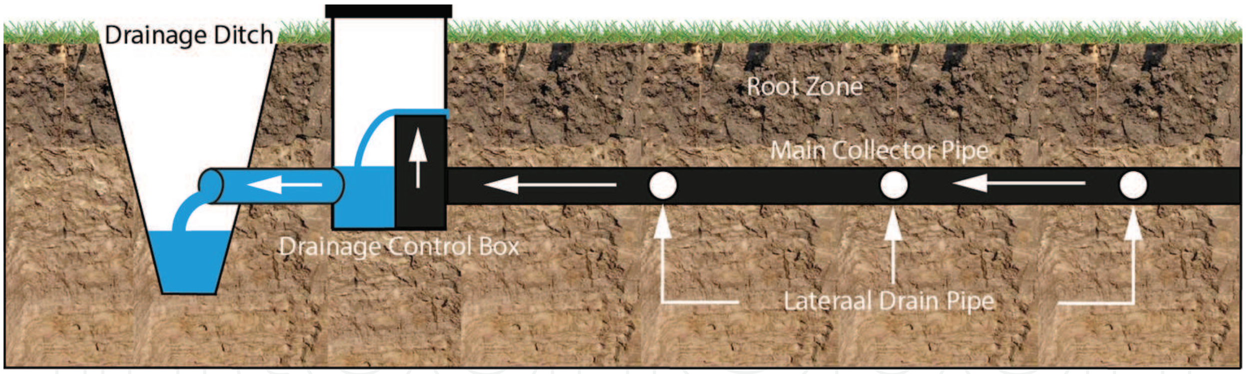

Figure 5. Climate Adaptive Drainage (CAD), with drains merging into a collector pipe, that discharges into a control box. The level in this box can be adjusted (manually or remote control), to anticipate on weather conditions in the next weeks or months.

using a collector between the drain and the receiving ditch. The collector (**Figure 5**) has an overlet shown in black of which the height can be varied. If this height above the base of the collector's overlet becomes larger, the groundwater becomes more shallow, closer to the soil surface and the root zone. Hence, adjusting the overlet height is the same as manipulating groundwater level.

CAD is beneficial to dynamically store water for the dry season. In regions with saline groundwater, and particular in areas where such saline groundwater seeps upward, as in deltas, dynamic drainage can be very useful to diminish the upward saline fluxes. With a shallow groundwater level enabled by CAD in the wet season, the upward saline seepage can be diminished. In the growing season, fresh water is consumed for evapotranspiration, and CAD can lower the saline water table, or perhaps be used to introduce better quality into soil.

6. Plastic mulching

Irrigation is often combined with other techniques that improve the water use efficiency (WUE), including several cropping and tillage techniques [39, 40]. Mulching involves putting a barrier between soil and atmosphere, using different materials such as crop residue, such as straw [41], leaves, paper, old carpet, plastic (**Figure 6**) or gravel. It may serve purposes other than water use efficiency as well, such as weed growth reduction.

In China, plastics have been used for many years after importing from Japan in 1970s. The technology has been transformed and developed and become important in agronomy, especially in NW China, where agriculture became much dependent on plastic mulching. In China, it is mainly used for cash crops, such as cotton, tobacco, medical herbs, bean nuts, loofah, and crops such as maize, bean, and potato.

Mulching serves various purposes.

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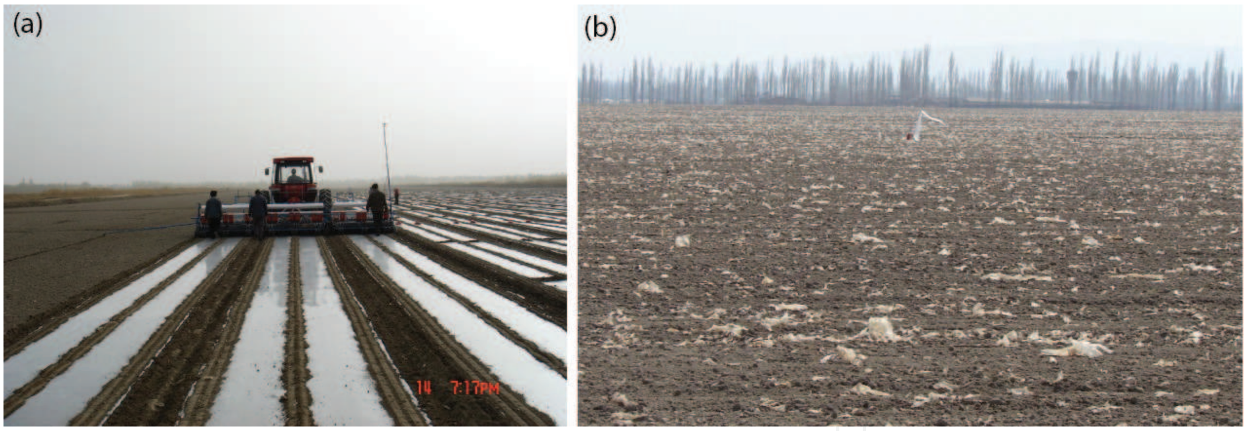

Figure 6. (a) Installation of plastic mulch and (b) postharvest field contaminated with plastics in Xinjiang, China.

1. Increasing soil temperature. Plastic mulching decreases heat exchange between soil and atmosphere, and leads to steadily increasing soil temperatures. For NW China, topsoil temperatures were found to increase 3–6°C in the top layer, and some heat is transferred into deeper layers. The sowing or planting time can therefore be earlier in spring (10–20 days) increasing the growing season. It is reported that crop yields can increase 20–30% compared with situations without plastic mulching and also crop quality can improve.

2. Reducing water evaporation and water conservation. The plastic blocks water vapor exchange between soil and open air and reduces soil evaporation. However, infiltration of rain water is not affected. Hence, soil moisture in 0–20 cm layer may increase 2% by plastic covering and in semi-arid and arid areas, around 1950 m^3 ha^{-1} water can be saved during the growing season.

3. Enhanced fertilizer efficiency. This beneficial effect is attributed to the reduction of nutrient losses via leaching, runoff and erosion. There are indications that soil available nitrogen, phosphorus and potassium might increase 30–50%, 20–30%, and 10–20%, respectively.

4. Improved solar light irradiation efficiency. Transparent plastic film and the water droplets which adhere onto this film improve soil absorption of light, benefitting photosynthetic intensity and postponing the senescence time of lower leaves of plant. It is reported that lower leaves can capture 12–14% extra catoptric light with plastic mulching, and tomato can capture 3–4 times more light, photosynthesis intensity may enhance 13.5–46.8%, and chlorophyll content in tomato may increase 5%.

5. Improving soil physical properties. Due to mulching, soil temperature rises, vapour pressure effects have been claimed to enlarge the pore sizes within soil particles, increase soil porosity, reduce soil bulk density and increase soil aggregate stability. This affects physical properties as well as soil fertilizer, water, atmosphere and heat balances, besides protecting the soil surface, avoid raindrop detachment and erosion of soil. Weed control may be less frequent and reduce soil compaction.

6. Improving soil microbial activity. By positive impacts on temperature and soil moisture, mulching is beneficial for soil microbial activity, microbial reproduction and growth, and organic matter decomposition and mineralization in the root zone, and improves nutrient availability. Also plastic use might inhibit diseases and pests.

7. Avoiding soil salinity. In saline regions, salts can be transferred by water evapotranspiration to the soil surface. By its water conserving effect, this transport is reduced.

Great changes have occurred since plastic mulching became use in China. Crop yields and quality improved. However, at the same time, plastic film residues have become a pollutant in the plough layer of agricultural soils. About 313.3×10^4 ha farmland is covered by plastic mulching, or 75% of the entire farming land of Xinjiang province, with an annual weight of plastics of 18.5×10^4 tons. In the main land for cotton planting, the plastic film residue is 25.32 g m^{-2} and has become a big problem for soil quality and crop growing. Recycling and natural degradation have therefore become important.

In China, plastic film residue recycling is mainly a human labour and machine-supported effort. About 60% of the plastic film residue is recycled with machinery and the main difficulty is the low intensity of residue and plastic pieces. To strengthen film intensity, China government has already issued a regulation since 1990s, entitled GB13735-92, for standard thicknesses, that changed from 0.008 ± 0.003 mm to 0.01–0.02 mm. However, the efficiency of machine recycling is limited. The paradox is that if the thickness increases, the cost will also be increased which farmers cannot afford. But if plastic film residue is recycled manually, the cost will become higher, especially in the regions with a labour shortage and efficiency of collecting plastic is low. Hence, machine supported recycling needs further development.

One of the concerns with all this use of plastics is that they may be gradually transformed into microplastics: particles smaller than 5 mm. Particularly for marine ecosystems, microplastics and their effects on various organisms have been investigated [42]. Also the plastics may interact with other pollutants accumulation in organisms [43], and possibly affect their impacts. For soil organisms, the study of microplastics is still in its initial stages as far as accumulation and effects is concerned, and one of the few papers addressing this issue is very recent [44]. Therefore, it is quite well possible, that bio-availability of pollutants and of microplastics, and their adverse environmentally and ecological effects may be linked, and this deserves closer investigation.

An alternative to deal with plastic residues in soil is to use biodegradable plastic film. However, such types of plastic film tends to be unstable for the range of natural conditions encountered, and therefore, these plastic films have not been applied widely yet. The use of organic mulch, such as crop residues, may be more sustainable from a chemical and biological perspective, as it would not lead to pollution. At the same time, it may have benefits regarding organic matter content, nutrient recycling and soil biology [45]. Although many studies are available regarding the effect of plastic cover on WUE, there are few studies available that compare the use of organic mulch to plastic covering. The results of these studies do not seem very promising for using organic mulches as an alternative for plastic, with lower water use efficiencies [46]. The use of plastic mulch was compared with the use of traditional practice and crop residue mulching [47]. It appeared that using plastic mulch not only led to higher yields in two of the three studied years, but also lead to significant soil water depletion in deeper soil layers, which may be explained by increased evapotranspiration [48]. However, in warmer climates, straw seems to conserve more soil water than plastic cover, although the effects on yield may differ [49, 50]. One study not only reported positive effects of straw mulching on salinity, but also mentioned that many uncertainties still remain [51].

7. Re-use of wastewater and soil sodicity

To make optimal use of resources, also marginal water, such as sewage or domestic wastewater is used for irrigation, in rural and peri-urban agriculture. However, this 'wastewater' suffers often of poor quality.

Compounds in wastewater that may be beneficial are nutrient elements, such as C, N, P, and K, that make wastewater irrigation similar to fertigation. Nutrient supply via wastewater is generally unbalanced, compared with the needs of crops. This may lead to accumulation in soil, or excessive leaching to groundwater and surface water.

Several other elements that may cause adverse (toxic) effects, for plants, soil fauna, animals and humans are boron, selenium, and (heavy) metals. It is worthwhile to mention the presence of Na in most domestic wastewaters. Sodium is often present due to the high salt concentration in the human diet. The hazard of Na-fluxes into agricultural root zones irrigated with wastewater cannot be judged well by only measuring the aqueous Na-concentration. As all cations, Na may sorb onto suspended materials such as organic matter (or organic carbon) and the load of Na that reaches soil with organic carriers might be appreciable. Moreover, also other cations (Ca, Mg) sorb, preferentially, onto suspended and dissolved (DOC) organic carbon. This may make the effect of Na larger, by suppressing the beneficial effect of Ca and Mg. Hence, the adverse effects of adding Na via domestic wastewater needs to be anticipated on the concentrations of Na, Ca, and Mg, as well as Biological Oxygen Demand (BOD), as a measure of suspended and dissolved organic matter.

The adverse effect of sodium is related to it being monovalent: Na^+. Accordingly, it may react with mineral and organic surfaces and surface groups, but different from multivalent cations as Ca^{2+}, Mg^{2+}, Fe^{3+} and Al^{3+}, it is less equipped to form charged bridges between different reactive surface groups. Therefore, why cementing agents as organic matter are known to detach from the sodic soil's solid phase and disperse and accumulate at the soil surface.

For similar reasons, sodic soils may be susceptible to structure deterioration. Being monovalent, Na-ions are less able to electrostatically neutralize the solid surface negative charge of soil clay colloids. Under saline conditions, this may not be so much of a problem, in view of the high concentration of ions that neutralize the electrostatic field of the negative clay colloids. If the salinity drops, diffuse double layers at the clay colloid surface expand (say an order of magnitude, of e.g. 40–400 nm) due to enormous swelling pressures [3]. Swelling causes very small pores (tens of nm) to swell at the expense of macropores, which are important for conveying water and (soil) air. Soil is then dominated by small pore sizes, and becomes almost impermeable to water. An impression of the reduction of the hydraulic conductivity due to decreasing salinity of a sodic soil is given in **Figure 7** [30]. In **Figure 7**, the sodicity of soil is expressed with the common metric of Exchangeable Sodium Percentage (ESP): the percentage of the cation exchange capacity that is occupied by sodium. Usually, a soil is called sodic if ESP exceeds 15%. As shown, the hydraulic conductivity decreases rapidly in case salinity decreases. In reality, the effect of sodicity on hydraulic properties is even more complex, as also the retention function is significantly affected.

Sodic soils can be found in the Central Plain of Hungary, in the Hortobágy region, developed after the regulation of the main rivers, one and a half century ago. These physically degraded soils, with distinct B_2t horizons at say 20–40 cm depth that virtually impede vertical water transport, are perhaps only useful for extensive agriculture. Due to the small thickness of the

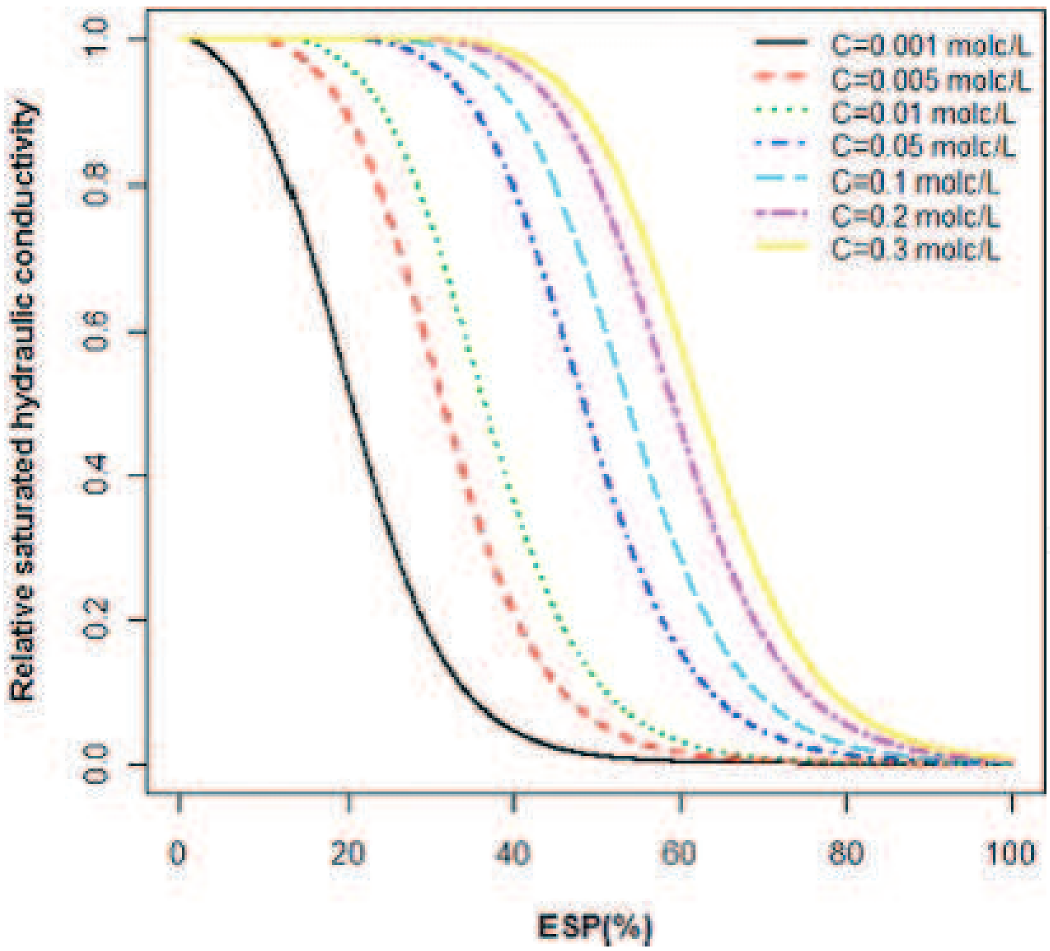

Figure 7. Relative saturated hydraulic conductivity as a function of ESP for different total salt concentrations in the soil solution (after Ref. [30]).

A-horizon, that supplies water for the crops (capillary rise from the ground water being impossible due to the B_2t horizon), the water supply is very small. Remediation during the past century proved quite challenging and a large part of the Hungarian central plain is still suffering from small yields. This indicates that sodicity is a process to avoid.

8. Conclusions

Water scarcity can be countered by improving water use efficiency, but as inevitably, irrigation leads to salinity under conditions of scarce fresh water, salts should be leached and removed. The Leaching Requirement (LR) shows how to irrigate and avoid salinity, for deep groundwater. Also for shallow groundwater, minimalist modelling as with LR may lead to very useful approximations for the estimation of the long term salinity of the root zone.

In many agriculturally important regions worldwide, such as deltas, groundwater is sufficiently shallow to be taken into account in assessments of salinization risks. Accordingly, drainage and irrigation dimensioning necessitate the consideration of groundwater levels, which are strongly related with capillary rise replenishment of root zone water. Simple guidelines, as proposed in this chapter, may become very relevant to avoid salinity. Furthermore, advanced dynamic approaches to drainage, such as Climate Adaptive Drainage (CAD), may be very useful for saving water till the dry season, suppressing saline upward seepage and capillary rise, and removing salts from the root zone more effectively. In the Dutch WaterNexus program (with the lead author), CAD is experimentally and theoretically investigated for this purpose.

Besides salinity, plastic mulching may have environmental risks in view of scarcely known impacts on environment such as soil ecology, and ultimately, human health. Likewise, sodicity, which is often a salinity-related issue, requires urgent attention: it is a stealthily developing condition, that cannot well be observed by the land user without advanced chemical tools, its adverse effects may occur quite suddenly, and remediation may require enormous efforts and significant resources. For these reasons, sodicity needs to be avoided as much and as early as possible. That requires expertise, excellent communication, and great awareness.

This chapter has been aimed at providing awareness and illustrating the value of theoretical understanding (e.g. the Leaching Requirement and further developments based on it). Such understanding is important to anticipate when currently common practice may be in conflict with long term sustainability.

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