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"Soil Salinization and Land Desertification"

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SOIL SALINIZATION AND LAND DESERTIFICATION

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SUMMARY

The salinization, or development of salt affected soils (saline and sodic),is a degradation process usually leading to desertification of lands. In general, in salt affected soils the water defficits make the survival of natural vegetation and crops difficult or impossible. These moisture deficits are due to the difficulties for the plants to use the water stored in the soil ("saline soils"), or to the difficulties for root development and for water infiltration into the soil ("sodic soils"). Although those processes may occur, and have ocurred under natural conditions, , they become accelerated, leading to secondary salinization, when, mainly in arid and semiarid environments, the soil water regime is drastically changed with the introduction of irrigation and/or drainage.

In many countries the irrigation has become a very important component of food production, sometimes the most important. The area with irrigation in the World has increased from 50 Mha in the year 1900 to 100 Mha in 1950, and to 250 Mha today. To this phenomena has also contributed the decrease of productivity and the increasing risks of dryland agricultural production on lands already affected by other degradation processes, mainly water erosion. The yearly loss of productivity, and desertification of irrigated lands, amounts to 1.5 Mha around the World, but the salinity problems, in different degrees, presently affect almost 50% of all the irrigated land. Although the affected areas by salinity are much less than the ones affected by other degradation processes like erosion, the social, economical and environmental effects are of the same magnitude, as a consequence of the high value and productivity of irrigated lands, and their coincidence with areas of large urban and industrial developments.

In arid and semiarid climates, the scarcity and erraticity of rainfall, together with the high evapo-transpiration rates, makes the water and salt balances favourable for the processes of soil salinization, specially under poor drainage conditions. These are the predominant conditions in the plains, valleys, deltas and coastal plains of the Mediterranean Region where irrigation has been introduced, because the soils and climate are favourable for a continued agricultural production of high productivity, if the soil moisture and salinity are well controlled.

The problems of secondary salinization are a consequence of non adequate water management by irrigation and drainage, under a particular set of conditions, including climate, crops, soils, fertilization, grounwater depth, water quality, and irrigation system. Therefore, the possibilities to preview the best conditions and alternatives of irrigation water management to prevent, control and decrease the problem of salinity, will depend on the understanding and modelling of the interactions of those factors for each set of conditions. This becomes more important when the limited water resources of good quality are preferentialy used to satisfy the urban and industrial requirements, and when the quality of surface and ground waters used for other purposes may be affected by the drainage effluents from irrigated lands. In this paper there is presented an improved version of a model developed by the author, which may be useful, among other things, to preview the best alternatives for the use and management of the available soils and waters, preventing the process of desertification by secondary salinization.

INTRODUCTION

Salinization, or development of salt affected soils, is one of the processes of soil degradation leading to land desertification. The salt accumulation may lead to a partial or complete loss of the soil capacity to provide the required amounts of water to plants, changing fertile lands to "deserts". Frequently, the salinization processes creates a practically irreversible chemical or physical internal soil degradation.

Worldwide more than 10% of lands are affected by some type and level of salinization, with 350 Mha already completelly "desertified". Although the salt affected soils may be found in almost any climate, they are more common in arid and semiarid climates, and in flat and low lands. It is considered that about 25 Mha of lands have been salinized through human intervention since the development of irrigated agriculture thousands of years ago (Szabolcs, 1989; WRI-IIED-UNEP, 1988).

The salinity problems appear as a consequence of salt acummulation in zones and depths where the soil moisture regime is characterized by strong losses of water by evaporation and transpiration, and by reduced leaching of the remaining salts. Although these processes of salinization may progressively develop under natural conditions where a combination of aridity and restricted drainage exists, they may only be accelerated when the soil moisture regime is drastically changed with the introduction of irrigation, without appropiate drainage conditions.

SALINIZATION AND IRRIGATED AGRICULTURE

Irrigation of agricultural lands has been considered for several milenia the most effective way to increase and regulate the crop production, specially in arid and semiarid zones. Frequently those benefits have not been sustainable mainly due to soil salinization. This is known from the ancient times, and it has been said that the salinization of large irrigated areas in the Mesopotamian Plain conduced to drastic decreases in food production, and was one of the main causes of the fall of the Sumerian civilization almost 5000 years ago. Both then and nowadays, the salinization of agricultural lands is a consequence of an inadequate combination of irrigation water management, and drainage conditions.

Salts, in variable amounts, are always present in irrigation waters. The input of salts through irrigation may reach more than 10 Mg/ha in one year. Most of them remain in the soil when the water is lost by evapo-transpiration. When those salts are not leached to the subsoil and lost through internal drainage, they will accumulate in the surface soil, reaching levels which may affect the plant growth. When the required leaching is not provided by the excess of rainwater, common situation in arid and semiarid climates, it is required to apply an excess of irrigation water for such purpose. If those excesses of water are not taken away by the natural or artificial drainage systems, probably the leached salts will come back to re-salinize the surface soil.

From the previous arguments it may be deduced that the introduction of irrigation in arid, semiarid, and ocassionally subhumid zones, will lead to soil salinization problems, unless there are provided adequate drainage conditions. The drainage practices to control salinity problems in irrigated areas were practically unknown until the beginning of this century, and only after 1945-50 they had a scientific base (Boumans,1987). The concept of leaching requirement, or leaching required to control salinity under tolerable limits (expressed as a % of the irrigation water applied), was introduced only in 1954 (USDA,1954). The application of all these recent advances have allowed in many cases to control salinization, and even to recover areas already affected by salts, finishing with the old axiom that irrigation would lead in any case to soil salinization.

Although the development of irrigated agriculture has been associated to the development of great ancient civilizations, its rapid expansion to large areas has been only in recent times. From about 8 Mha of land with irrigation in the whole World in 1800, the irrigated area was extended to 50 Mha in 1900, ant to almost 250 Mha at present, with projects to expand it to 350-400 Mha in the next twenty years. Presently, 80-1000 million people in the World have activities related to irrigated agriculture, which produces about 35 % of the food in only 18 % of the cropped area (Szabolcs,1989; WRI-IIED-UNEP,1988). The main factors responsible for such accelerated growth of irrigated agriculture are:

1)The need to intensify the agricultural use of lands for satisfying the increasing food requirements of people.
2)More than 75% of the World agricultural lands are in arid, semiarid and subhumid zones, where the scarcity and erraticity of rainfall leads to very poor and risky production of rainfed crops.
3)The more or less irreversible loss of productivity in large areas of rainfed agricultural lands affected by some other processes of soil degradation, mainly water erosion.

In many cases, the irrigated agriculture developed in the lower and flatter lands of valleys and watersheds, makes use of soils formed on sediments originated from past and present processes of erosion in the higher and steeper lands of the watershed. It also uses surface and ground waters feeded by runoff losses from those degraded lands, due to their low rainwater intake rates and reduced moisture retention capacity.

Regretfully, the fast development of irrigated agriculture has been, and still is, associated to an increase in soil degradation by salinization processes. This happens despite our generally good knowledge about how to predict, control, and revert such processes. The precise evaluation of salt affected areas of human origin is sometimes difficult (ISRIC-UNEP,1990), because the problems of salinization develops progressivelly, and sometimes they are only visually apparent when they have reached conditions difficult to recover. It is known that every year about 1.5 Mha of irrigated land lose 25-50% of their productivity due to salinity; and that 50% of the whole irrigated area in the World suffer losses of productivity due to salinization processes. Taking into consideration the great investments required for the development of irrigated agriculture, and their high contribution to the World food production, we may conclude about the great importance of land degradation by soil salinization from the economical, social and environmental point of views; and about the urgent requirements to prevent and control the processes leading to such degradation.

SALINIZATION IN THE MEDITERRANEAN REGION

In the predominant semiarid mediterranean climate rainfall is impredictable, and with great variation from one year to another. Therefore, the probabilities of low yields, and the risks of complete losses, of rainfed crops is very high. In addition to that, the high erosivity of rainfall, together with poor soil cover and inadequate land use and management, have led to advanced land degradation by water erosion in the predominantly hilly topography of the region (Chisci,1990), decreasing the potential for producing rainfed crops. This, added to the increasing markets for some agricultural products requiring irrigation, explains why the irrigated area in the Mediterranean Europe has increased three times since the beginning of the century.

The development of irrigation has been mainly in flat alluvial lands, bottom of valleys, and coastal plains and deltas, generally with slopes less than 5%. Those areas, under the predominant mediterranean climate, are frequently affected by floodings and sedimentation. In those lands, with low risks of erosion (Rubio and Sanroque,1990), the main potential problem of desertification is soil salinization, due to the combination of climate, drainage, quality and management of the irrigation waters.

The needs to increase the areas with agriculture under irrigation, and the increasing problems of salinization in irrigated lands, in most of the mediterranean countries, has been already recognized (Albaladejo,1990; Chisci, 1990; Generalitat Valenciana,1987; Pereira et al,1987; Yassoglou,1990). Irrigation developments have not only reduced the production risks due to moisture deficits, but have also allowed cropping in the summer months, and the introduction of perennial fruit crops. With the high sun radiation in the Mediterranean Region, the irrigated crops are usually highly productive, if there are maintained adequate water and salt balances in the soil. The area under irrigation is already in some mediterranean countries more than 1/4 of the total cropped area. About 25% of the 6 Mha of irrigated lands in the Mediterranean Europe are desertified by moderate and severe degrees of salinity (WRI-IIDE-UNEP,1988). Compared with this, 39% of the 76 Mha with dryland agricultural production (40 Mha with crops), are desertified mainly due to water erosion. The last twenty years, the irrigated area has been continuously increasing, while the area with rainfed agriculture has decreased almost 20%.

Frequently the areas with irrigated agriculture are located close to zones with high urban and industrial developments, which demand and consume most of the scarce water of good quality. For irrigation of crops there are sometimes only left waters of poor quality, mainly saline groundwaters and partially treated urban and industrial effluents. The over pumping of groundwaters in coastal plains frequently leads to intrusion of sea water in the aquifer, gradually increasing the salinity of the pumped water (Generalitat Valenciana,1987). Similar results are obtained when the over explotation of aquifers brings to the pumping level deeper and more saline groundwater.

The excess of water required to leach salts from the soil, to reclaim or to prevent salinization, may cause other environmental problems derived of the disposal and further use of that water. The problem is agravated because those leachates may contain not only salts, but also residues of fertilizers and pesticides, which are generally used in large amounts in the intensive irrigated agriculture. They may contaminate surface or ground waters to be used for human, industrial, or agricultural purposes. In those cases, the practices and systems of drainage and irrigation must pursue a maximum efficiency in the use of irrigation water, reducing the possibility of losses and contamination of other waters, but keeping at the same time the salts at depths not reached by the crop roots. This has to be sometimes combined with systems for disposal of drainage waters before they mix with others.

Desertification of lands by soil salinization in the Mediterranean Region may be worsening at increasing rates in the next decades, due to the previewed increase in irrigated areas, and to the increasing scarcity of good quality waters, unless some preventive actions are urgently taken. The problem may be aggravated due to the global climatic changes, previewed for the near future. It has been speculated that in the Mediterranean Europe those climatic changes would double the salt affected areas in the next 50 years, mainly in the same zones where salinity is already a problem (Szabolcs,1990). This would be caused by an increase in the aridity index, affecting the moisture regime and salt balance in the soil, with less leaching and more salinization. The increase in aridity would also force an increase in the irrigated areas, and the use of waters of poorer quality. Another previewed effect on the salinization of lands would be due to the rise of sea level, by flooding the low lands in deltas, and by increasing the intrusion of saline water in coastal aquifers.

Another reasonings, preview some positive effects of the future global climatic changes on the crop growth and productivity, due to the increase of CO_2 in the atmosphere (Goudrian and Unsworth,1990). Under greenhouse conditions it has been proved that higher levels of CO_2 increases its assimilation by plants, even in conditions of moderate soil moisture stress, due to low moisture (matric stress) and/or salinity (osmotic stress). This would happen because the CO_2 and the transpired water follow the same physical pathway through the stomata. The final result is an increase in the efficiency of water use, mainly due to a decrease in the transpiration rates (C_4 plants), or to a stimulation in the rate of CO_2 assimilation (C_3 plants). These effects would indirectly increase the availability of photosinthetic products for osmotic adjustments required to keep cell turgor in more saline soils. Nowadays, some of these effects are obtained with the increasing use of greenhouses for different crops in the Mediterranean Region.

It may be concluded, that although at present time the area desertified by human induced (secondary) salinization in the Mediterranean Region is less than the affected by other degradation processes like erosion, the importance of both problems, from the economical, social and environmental points of view are comparable. This is due to the higher value and productivity of the affected irrigated lands, and their location generally in areas with high urban and industrial developments, competing with agriculture for the use of the scarce available water resources.

SALINE AND SODIC SOILS. CHARACTERISTICS AND EFFECTS

In general, all soils with problems directly or indirectly derived from the amounts and kind of salts in solution are referred as "salt-affectd soils". The resulting problems may be very different, depending on the geochemical processes involved in the development of salinization. This applies both to the salinization developed through natural processes (primary salinization), and to the salinization induced by human intervention (secondary salinization). In both cases, the main responsible factors are the concentration and the relative composition of salts in the surface and ground waters, and the changes they may suffer in soil solution. These changes are dependent on the soil moisture regime, which is a consequence of the drainage and climate conditions. Drainage is the result of the hydraulic properties of the soil profile, of the groundwater depth, and of the landscape position. Rainfall and evapotranspiration are the main climatic factors to be considered. The development of secondary salinization, in different soils and climates, is generally caused by drastic changes in the soil moisture regime due to the introduction of irrigation with drainage restrictions.

Both in surface and groundwaters, and in soil solution, most of the salts are a combination of the cations Ca^{++}, Mg^{++} and Na^{+}, and of the anions HCO_3^-, Cl^- and $SO_4^{=}$. In some highly fertilized soils, the anion NO_3^- may also accumulate in soil solution. The main natural source of the predominant salts is the weathering of minerals in the earth crust, the rainfall in coastal areas, and the dissolution of fossil salts in some geological formations of marine origin. The human intervention brings additional salts to the soils through irrigation water, residual waters, and fertilization. The differences in amounts and kind of salts accumulated in soil solution result in "salt-affected soils" of varied chemical, physical and physico-chemical properties, having different management requirements for their prevention, use and reclamation.

Based on the main effects on soils and crops we may classify the "salt-affectd soils" in "saline soils" and "sodic soils". Traditionally the "sodic soils" have been called "alkali soils", although these include only the sodic soils with presence and accumulation of Na bicarbonates and carbonates and pH higher than 8.5-9.0. There are other soils with properties of sodic soils with lower pH and lower relative levels of Na than the alkali soils (Pla,1988).

The "saline soils" are those where the salt content and osmotic pressure of the soil solution do not allow the absorption by the crop of a great portion of the soil water, and do not show any direct effect on the soil physical properties. The main consequence is the partial or complete reduction in plant growth due to physiological water defficits. For practical purposes, the salt concentration is expressed in terms of electrical conductivity (units of dS/m:deciSiemen/meter at 25°C) in soil saturation extract (USDA,1954). One dS/m is aproximatelly equivalent to a salt concentration in solution of 10 meq./liter, and to an osmotic pressure of 36 KPascals.

It is well known that the soil moisture stress for plants is composed by the matric stress, which increases when the soil moisture decreases, and the osmotic stress, which increases when the salinity in soil solution increases. Both stresses are more or less additive. Therefore, one approach to reduce the effects of salinity would be to maintain the matric stress as low as possible, through frequent or continuous irrigation (see fig. 1). Another approach would be to plant salt-tolerant crops, which are able to grow and produce economical yields even at high soil moisture stresses, through adjustments in their transpiration rates or in the osmotic pressure in their cells.

As a consequence of the selective accumulation of some specific electrolites in soil solution, in some occasions, specific nutritional or toxic effects are associated or precede the more general osmotic stress effects. This is the case with some sensitive crops, when chloride, sodium, and sometimes boron, reach critical levels in soil solution. In occasions, the concentration of elements like selenium in some grasses, may affect the health of cattle eating them.

Frequently, the salinity effects on plants are only visible after the crop yields have been strongly decreased. This gradual effect of salinity on yield may be calculated (Mass and Hoffman,1977):

$$Y/Ymax. = 1 - b\ (EC_{SE} - EC_{SE}\ max.)$$

where: Y:Actual yield; Ymax.:Yield in non-saline soil; ECmax.:Electrical conductivity in soil saturation extract when Y starts decreasing:intercept in the y axis of the straight line relating Y/Ymax. and EC_{SE}; b:slope of the Y/Ymax. vs EC_{SE} line, characteristic for each combination of crop, climate and irrigation management.

Development of "saline" soils is more common in arid and dry semiarid climates, with LGP<120 days(see table 1). The methods for prevention or reclamation of these soils are based on the leaching of the excess of accumulated salts, taking maximum advantage of temporary (seasonal) surplusses of rain water, and applying more irrigation water than the crop requirements. Depending on the circunstances, this leaching may only pursue the displacement of salts to depths in the soil profile not reached by crop roots, or their deffinitive displacement by deep drainage. The first alternative requires of a carefull control in the management of irrigation water and of the groundwater level. In some ocassions the leaching of "saline" soils may result in the development of "sodic" soils, as a consequence of the salt composition in the original soil or in the water used for leaching, and also due to the particular soil mineralogy.

In these cases, the reclamation of saline soils must follow some of the practices recommended for reclaiming sodic soils.

The "sodic soils" include those where the accumulation of high Na levels, sometimes with Mg, both in solution and exchangeable, in relation to the levels of Ca+Mg and total salinity, leads to deleterious effects on their physical properties. The main consequences are drastic reductions, both in the saturated hydraulic conductivity of the soil and in the surface water intake rate. In practice it has been proved very convenient to express the "sodification" levels in terms of "sodium adsorption ratio" (SAR) in the soil saturation extract (SE) (USDA,1954):

$$SAR_{SE} = Na_{SE}/(Ca_{SE}+Mg_{SE})^{1/2}$$

where Na, Ca and Mg are the concentrations of those elements in the saturation extract (SE) in milimols/liter.

The effects on soil physical properties are in some cases mainly due to the dispersion of clay and silt particles in the surface soil. This produce inmediate surface sealing, and with time may lead to the complete and irreversible plugging of pores by the dispersed particles in a soil layer close to the surface, which becomes almost impermeable to water, and extremely compacted and hard when it dries out. These effects are more common in soils with high contents of silt and/or low swelling clay (hydrated micas, caolinite), which may be dispersed at relativelly low levels (5% or less) of exchangeable Na if the total salinity in soil solution is maintained very low (Pla,1988).

In other cases, the harmful effects on soil physical properties also includes the blocking of pores by reversible swelling of clays under wet conditions. This generally requires of higher levels (10-15%) of exchangeable Na, and of swelling clays, and generally comes together with high soil pH and accumulation of salts (Na bicarbonates and carbonates) of alkaline hydrolisis. These soils have been also called "alkali soils", and some times "black-alkali soils" due to the dispersion and surface deposition of black organic matter. When the surface soil dries out and the swelling effect disappear, they generally develop deep cracks and a prismatic or columnar structure. Higher salinity levels in the soil solution, or in the percolating solution, decrease the dispersion and swelling effects of Na . The critical levels of salinity and Na leading to sodicity effects, mainly depend on the content and nature of clays in the soil, and on the kind of predominating effects (dispersion or swelling).

The main negative effects of sodic soils on crops are due to the decreased infiltration and storage of water in the soil, to the increase of soil moisture at wiltting point, to poor and shallow root development, and to extended periods of defficient soil aeration. All these effects usually conduce to restrictions in water and nutrient supply to the crop. In some cases the maximum possible soil water intake is less than the accumulated potential evapo-transpiration of plants (Fig.2), making impossible even their survival. Some additional effects are due to poor root development or high pH, creating different nutritional problems. It is also common that many sodic soils, sooner or later become saline, because the very low soil permeability do not allow effective leaching of the salts continuously incorporated by the irrigation water. Therefore, the use of sodic soils is usually restricted to crops like rice or some grasses, which are able to grow under almost continuous flooding conditions. Their reclamation, and also their prevention in many cases, require the use of chemical ammendments before leaching. Those ammendments are mainly acid salts of Ca like gypsum, or acid products, and may be added to the irrigation waters or directly to the surface soil. The Ca from the applied product, or the Ca from the carbonates precipitated in the soil and dissolved by the acid, replace the exchangeable Na, which has to be afterwards leached from the soil solution. For leaching to be effective, there is required to improve the water intake and percolation rates in the soil profile to values higher than evaporation rates.

It may be concluded that there are not precise limits of salts and sodium to classify salt-affected soils (saline or sodic), and that the limits proposed in the past (USDA,1954) may be only used as a general reference, and never to guide specific irrigation management, or reclamation practices. The critical values may be very variable depending on the particular combination of soil, climate, crop and management. The same variability exist in the possibilities of prevention and reclamation of saline or sodic soils. Table 1 shows the main general conditions which may lead to the development of different kinds of saline and sodic soils. Additionally, some more specific conditions previous to irrigation (Pla and Florentino,1983), like presence of fossil salts at shallow depths in the soil profile, or shallow saline groundwaters, may also influence the kind and degree of soil salinization. Figures 3a-3e represent profiles of the different salt-affected soils developed with irrigation under the conditions shown in table 1.

PREDICTIVE MODEL FOR SOIL SALINIZATION

The problems of secondary salinization, leading to saline or sodic soils, are mainly due to poor water management (irrigation and drainage) in relation to a particular combination of climate, soil, crop, fertilization practices, groundwater level and salinity, quality of irrigation water, and irrigation system. Today there are known methods and technical possibilities to reclaim salt-affected soils, but in general they are too costly. When socioeconomic problems justify the reclamation, still we may have difficulties to do it, derived from the scarcity of water of good quality for leaching, or from potential problems of contamination of surface and ground waters used for irrigation or for domestic and industrial purposes. All these situations are very common in the arid and semiarid zones under irrigation in the Mediterranean Region. Therefore, it would be more convenient and economical to pre-stablish, through appropiate predictive models, which would be the best alternatives for irrigation water management to prevent salinization problems for each combination of climate, soil and available - quantity and quality - irrigation water. This would still be more important if there is a high competition for the use of scarce resources of good quality water, when the quality of the available water is poor, or when it is necessary to reduce the effluents of drainage water to a minimum.

To predict salinization problems the main pre-requisite is to identify the source of salts, and to characterize the main factors determining the regime of water and salts in the soil. This is not easy, because the hydrological and chemical conditions involved in the process of salinization are usually very complicated. Therefore, we have to simplify some of them, to be able to develop models that can be put into practice.

Without adequate leaching and drainage it is not possible to control soil salinization under irrigation. That is why we base our prediction model in the so called "leaching fraction" (L), which integrates in one figure the actual or required water and salt balances. The leaching fraction is defined as the fraction of infiltrated water which eventually is lost as internal drainage water after flowing through the soil below the root zone. It was originally introduced in 1954 (USDA,1954), as a quantitative expression of the leaching required to control soil salinity below some critical level. Although the concept remains essentially the same, its calculation has become more precise through the years (FAO,1976; Pla,1968,1983,1988; Pla and Dappo,1974;

Rhoades,1968,1984), and has been extended to the prediction of soil sodicity. These improvements have been possible thanks to a better knowledge of the relations among irrigation, drainage and salinity, taking into consideration in some cases the previewed precipitation or dissolution of salts in the soil profile, and the possibilities of sodification, besides salinization. This allows a more accurate calculation and planning of the irrigation and drainage requirements and practices.

The equations for the calculation of L presented in table 2, are the product of succesive approximations (Pla,1968,1983,1988; Pla and Dappo,1974) based on accumulated experiences and validations, in different agroecological zones, during the last 25 years. In this ocassion we introduce new independent balances of Ca and Mg, in order to preview some specific cases where the accumulation of Mg salts may be a critical factor. All calculations are based on an independent balance of the more common elements in irrigation waters and in soil solution, taking into consideration the possibilities of salt precipitation or dissolution under the prevailing conditions in irrigated soils. To do that, there are used as limiting conditions both the critical salinity levels for different crops and climates, and the critical sodium levels for different soils and concurrent salinity levels.

The proposed model first leads to preview the conditions for development of "salinity" or "sodicity". This prediction is very important, because the requirements for management or reclamation of those two kinds of salt-affected soils are very different. The independent balance of the different ions permits to predict the accumulation in soil solution of some elements like Cl^-, Na^+, etc. which may be toxic to some crops before the development of general problems of salinity or sodicity. With the same approach it is possible to preview the conditions leading to more precipitation or dissolution of salts of limited solubility (Ca and Mg carbonates, and Ca sulfate), and the effects of this on the leaching requirements to control salinity and sodicity in the soil root zone. This has also a high practical importance to define the conditions for the application of the concept of "reduced leaching" (Rhoades et al,1974), when it is important to decrease to a minimum the volume of drainage efluents, without reaching critical salinity levels in the root zone. Additionally, with the model it is possible to predict the characteristics of the drainage waters, and the possibilities and conditions for their further use in irrigation (Rhoades et al,1988), or for other purposes.

Using the calculated values of L, based on the different critical salinity and sodicity levels for crops, soils and drainage waters, it is possible to deduce the irrigation (hR) and drainage (hD) requirements in relation to the water requirements of a crop (hET) in a particular climate:

$$hR/hET = 1/(1-L) \qquad hD/hET = L/(1-L)$$

Figure 4 shows how the requirements of irrigation water, and the volume of drainage water increase with increasing values of the leaching fraction. The "effective leaching fraction" (LF) may be calculated from L, using a factor (F) for leaching efficiency. In practice we define this factor as the relation between the salt or sodium concentrations in the soil saturation extract - used to fix the critical levels - and their concentratiom in the drainage effluents (Pla, 1983). The value of F is generally less than one, because the leaching water do not usually move uniformly through the soil mass, compared to the uniform mixing of soil and water in the saturated paste. The lower values of F are generally found in highly structured clay soils, specially if large cracks develop on drying, and irrigation is applied at large intervals. The higher values of F, close to one, are common in sandy or silty soils, with poor structural development, and when there are used high frequency or continuous irrigation systems.

The requirements of irrigation management (Pla,1988), are mainly derived of the relations between duration (tR) and frequency (tBR) of irrigation, and may be calculated from the values of leaching fraction (L) and intake rate (I) of irrigation water. The decission about using conventional, high frequency, or continuous (flooding or drip irrigation) irrigation systems will be based on that value. Figure 5 shows the relations between tR/tBR and L for different I/hET ratios. It may be appreciated that high values of tR/tBR may be a consequence of high L. This happens when the salinity of irrigation water is high and/or the crop tolerance to salts is low, but also when the I/hET values are very low, as it happens when there are sodicity effects. When the calculated values of L or tR/tBR are higher than one it means that the given conditions are impossible to reach.

In our model, the salt balance for the calculation of L is based on average equilibrium values of salinity or sodicity to be reached in the root zone. There would be some possibilities to reduce temporarily the calculated values of L and hD, when through irrigation or sowing systems and practices, the excess of salts remaining in the soil profile are maintained away from the zone or depth with higher root development. Figures 6a-6f show some of the results of applying the proposed model to some selected waters (Table 3) being used for irrigation in the Mediterranean Region (FAO,1976; Giraldez y Cruz,1973; Martinez,1978). The water II represents a typical example of groundwater salinized by sea water intrusion. Water Vg is the same water V with addition of an ammendment of 35 g/m^3 of gypsum (Pla,1969) in order to reduce its potential sodicity effects on the soil. The graphs show the levels of salinity, sodicity, chlorides, and of Ca and Mg salts to be reached in soil solution for each effective leaching fraction (LF). There is also shown the % of salts added with irrigation water, that will precipitate in the soil as Ca and Mg carbonates and as Ca sulfate, at each LF value. The great differences among waters may be appreciated. Therefore, the individual analysis of each case in relation to particular conditions of climate, soils, crops, available water, possibilities and problems of drainage, etc. would lead to different conclusions about the more convenient alternatives of irrigation management.

As an example, figure 7 shows what would be the monthly irrigation and drainage requirements to control salinity in the surface 50cm of a medium texture soil, in a dry semiarid mediterranean climate. Those requirements were calculated both for the water III, slightly saline, and with a high tendency to precipitate carbonates and gypsum (see figure 6c) at medium soil salinity levels; and for water II, highly salinized by see water intrusion in the aquifer. Under the selected average conditions, the rainfall water would only help to reduce the needs of irrigation water to cover crop and drainage requirements, but it would not provide by itself any water surplusses for effective leaching of salts in any month of the year. The strong differences among the two irrigation waters demonstrate how important is to preview those effects, in order to take beforehand the right decissions for the use and management of water from coastal aquifers, to prevent their salinization.

CONCLUSIONS

The desertification of lands by soil salinization processes, which is already affecting large areas in the whole World, naturally or through the human influence, is specially a growing problem in large arid to semiarid areas of the Mediterranean Region. The problem has a tendency to become worse derived from the pressure to extend irrigated areas, due to the great limitations and risks of dryland agricultural production under the predominant climatic conditions in most of the region. The scarcity of water resources of good quality in the region, and the competing use of them for urban and industrial purposes, is leading to the increased use for irrigation of more saline waters, sometimes as a consequence of the over-explotation and salinization of aquifers, and in some others due to the use of more or less pre-treated residual waters. In ocassions the drainage effluents from an irrigated area are, or have to be used again, directly or mixed with other surface or ground waters, for irrigation or other purposes, including human consumption. To minimize the contaminating effects of those drainage effluents, many times charged with salts, but also with residues of fertilizers and pesticides, used in large amounts in the very intensive irrigated agriculture, it is important to be able to precisely calculate the minimum drainage requirements to reduce those efluents, without reaching critical soil salinity levels.

Generally, the reclamation of salt-affected soils is difficult and very expensive. This is still more complicated when the sources of good quality waters are scarce, and there are possibilities of contamination of waters required for other uses. Therefore, the prevention of soil salinization may be preferred to reclamation. The proposed predictive model, has proved to be reasonably good to predict the type and approximate levels of soil salinization problems, that would develop under different combinations of the main hydrological and chemical factors and processes involved. It may also be used to calculate the requirements, and to deduce the best alternative practices, for irrigation and drainage, not only to prevent soil salinization and sodification, but also to control some other related environmental problems. In order to facilitate the use of the model, and to allow a faster analysis of all alternatives and their probable effects, it has been developed a PC computer program based on it.

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LIST OF TABLES

Table 1

Conditions	(A)	(B)	(C)	(D)	(E)
IRRIGATION WATER					
Concentration:	(High)	(Medium)	(Low)		
(EC):	> 2 dS/m	1-2 dS/m	< 1 dS/m		
Composition:	Cl>S>B Na>=CA	S>=Cl>B CA>Na	B>=S>Cl CA>=Na		B>S>Cl B>CA Na>=CA
DRAINAGE	(Variable)		(Very restricted)		(Restricted)
Soil Perm.(I):	1-50 mm/hour		< 1 mm/hour		< 5 mm/hour
Groundwat.level:#	<1.5 m		< 0.5 m		< 1.0 m
CLIMATE	(Ar.-DSAr.)		(Ar.-DSAr.)	(DSAr.-SH.)	(Ar.-HSAr.)
IMA (P/ETP):	< 0.5		< 0.5	0.5-1.0	< 0,8
LGP (P>(ETP/2)):	< 120 days		< 120 days	120-270 days	<180 days
Resulting problem					
SOIL SOLUTION	(Very saline)		(Mod.saline)	(Sligh.saline)	(Var.sal.)
Concentration(EC):	> 8 dS/m		> 4 dS/m	< 4 dS/m	> 2 dS/m
Composition:	Cl>>S>>B Na>CA	Cl>=S>>B Na>=CA	S>Cl>B Na>CA	(*) S>=B>Cl Na>>CA	B>=S>Cl Na>>CA
	(A)	**(B)**	**(C)**	**(D)**	**(E)**
pH	< 8.5		< 8.5	> 7.5	> 8.5
PRECIPITATED SALTS:	CAC, CaS		CAC, CaS	CAC	CAC
EXPECTED POTENTIAL KIND OF PROBLEM:	"S A L I N I T Y"			"S O D I C I T Y"	

Cl, S, B, Na, Ca, CA : Chlorides, sulfates, bicarbonates, Na, Ca, and Ca+Mg respectivelly, in water or soil saturation extract. CAC, CaS : Ca+Mg Carbonates and Ca Sulfate, respectivelly, precipitated in the soil. EC : Electrical Conductivity. I : Minimum Water Intake Rate. IMA : Index of Moisture Availability = Rainfall/Potential Evapo-Transpiration (P/ETP) in the whole year. LGP : Length of Growing Period = Days with rainfall higher than 1/2 of the potential evapo-transpiration, and average daily temperatures higher than 5ºC. Arid Climate(Ar.) : LGP 0-74 days; Dry Semi Arid(DSAr.) : LGP 75-119 days; Humid Semi Arid(HSAr.) : LGP 120-179 days; Sub-Humid(SH.) : LGP 180-270 days. (#) Permanent groundwater level, or presence of strata impeding or restricting the internal drainage. (*) Change of composition under anaerobic conditions ($2Na^+ + SO_4^= + 2C + 2H_2O = S^= + 2NaHCO_3$).

Table 2

When: $B \le (Ca+Mg)$

$$LF(ST) = (Na+Ca+Mg)/ST_{SE}; \qquad LF(Na) = (2\,Na^2)/(SAR_{SE}^2 \,.\, (Ca+Mg))$$

$$Na_{SE} = Na/LF\ ;\ Ca_{SE} = Ca/LF\ ;\ Mg_{SE} = Mg/LF\ ;\ Cl_{SE} = Cl/LF$$

If: $10\,LF < B$ and $30\,LF \ge CaS$

(Precipitation of Ca and Mg carbonates)

$$LF(ST) = (Na+Ca+Mg-B)/(ST_{SE}-10)$$

$$LF(Na) = \frac{((SAR_{SE}^2.(Ca+Mg-B)^2)+(80\,Na^2))^{1/2}}{20\,SAR_{SE}} - \frac{(Ca+Mg-B)}{20}$$

$$Na_{SE} = Na/LF;\ Ca_{SE} = \frac{10(Ca+Mg-MgB)}{(Ca+Mg)} + \frac{(CaS+CaCl)}{LF};\ Mg_{SE} = ST_{SE}-(Na_{SE}+Ca_{SE})$$

$$Cl_{SE} = Cl/LF; \qquad (Ca+Mg)Cp = (Ca+Mg) - LF(Ca_{SE}+Mg_{SE})$$

If: $10\,LF < B$ and $30\,LF < CaS$

(Precipitation of Ca carbonates and sulphates)

$$LF(ST) = (Na+Mg+CaCl)/(ST_{SE}-40)$$

$$LF(Na) = \frac{((SAR_{SE}^2.\ (Mg+CaCl)^2)+(320\,Na^2))^{1/2}}{80\,SAR_{SE}} - \frac{(Mg+CaCl)}{80}$$

$$Na_{SE} = Na/LF;\ Ca_{SE} = 40+(CaCl/LF);\ Mg_{SE} = Mg/LF;\ Cl_{SE} = Cl/LF$$

$$CaCp = B - 10\,LF; \qquad CaSp = CaS - 30\,LF$$

If: $10\,LF \ge B$ and $30\,LF < CaS$

(Precipitation of Ca sulphate)

$$LF(ST) = (Na+Ca+Mg-CaS)/(ST_{SE}-30)$$

$$LF(Na) = \frac{((SAR_{SE}^2.(Ca+Mg-CaS)^2)+(240\,Na^2))^{1/2}}{60\,SAR_{SE}} - \frac{(Ca+Mg-CaS)}{60}$$

$$Na_{SE} = Na/LF;\ Ca_{SE} = 30+((Ca-CaS)/LF);\ Mg_{SE} = Mg/LF;\ Cl_{SE} = Cl/LF$$

$$CaSp = CaS - 30\,LF$$

When: $B > Ca+Mg$

(Presence of Na bicarbonate and precipitation of Ca and Mg carbonates)

$$LF(ST) = Na/(ST_{SE}-Ca-Mg); \qquad LF(Na) = Na/(SAR_{SE}.((Ca+Mg)/2)^{1/2})$$

$$Na_{SE} = Na/LF;\ Ca_{SE} = Ca;\ Mg_{SE} = Mg;\ Cl_{SE} = Cl/LF;\ NaB_{SE} = NaB/LF$$

$$(Ca+Mg)Cp = (Ca+Mg).(1-LF)$$

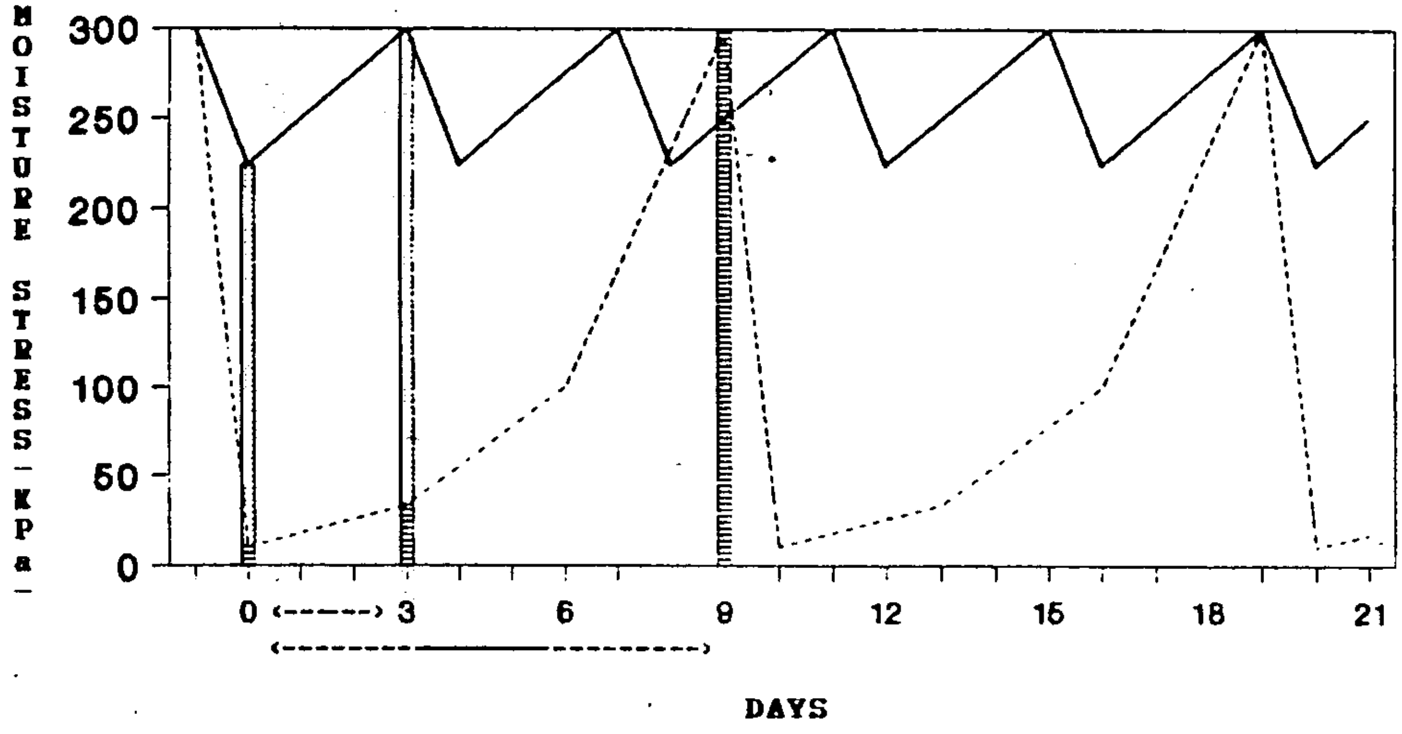
Ca, Mg, Na, B, S, Cl, MgB (B-Ca-NaB), NaB (B-Ca-Mg), CaS (Ca-B-CaCl) and CaCl (Ca-B-S) : Ca, Mg, Na, Bicarbonates, Sulfates, Chlorides, Mg Bicarbonate, Na Bicarbonate, Ca Sulfate and Ca Chloride in meq./liter in irrigation water, respectively; L : Leaching fraction: LF : Effective leaching fraction (F<=1); ST_{SE}, Na_{SE}, Ca_{SE}, Mg_{SE}, Cl_{SE}, NaB_{SE}, SAR_{SE}: Salinity (total), Na, Ca, Mg, Chlorides and Na Bicarbonate (meq./liter), and Sodium Adsorption Ratio (SAR = $Na/((Ca+Mg)/2)^{1/2}$) in $(mmols/liter)^{1/2}$, in saturation extract (SE), resp.; (Ca+Mg)Cp, CaCp and CaSp : (Ca+Mg) Carbonates, Ca Carbonate and Ca Sulfate, resp., precipitated(+) or dissolved(-) in the soil. in meq/liter of irrig. water.

Table 3

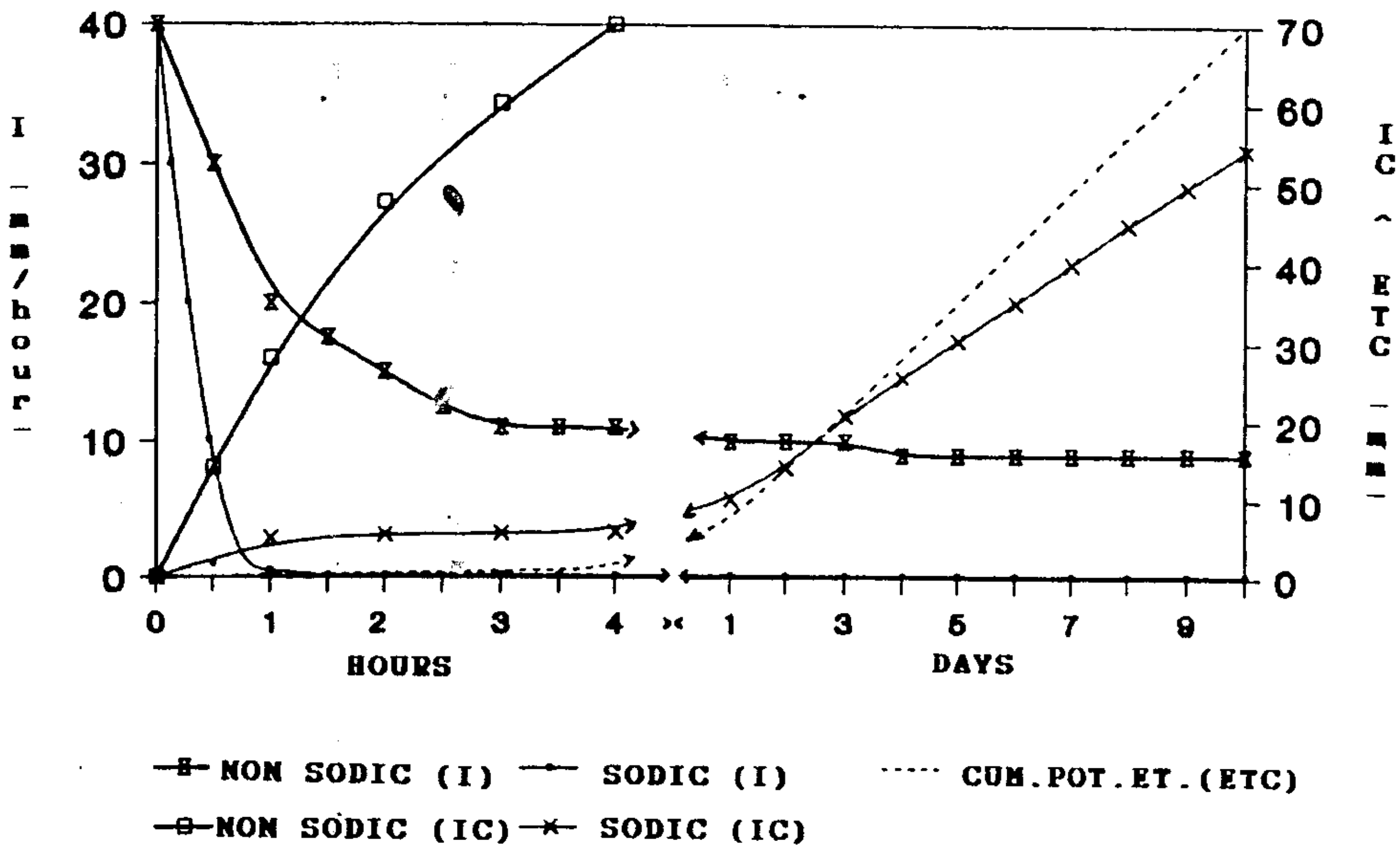
WATER	Source	EC dS/m	Ca++	Mg++	Na+	HCO3-	SO4=	Cl-	SAR
			meq./liter						
I	Well	2.7	5.6	3.9	19.5	8.7	7.5	11.7	8.9
II	Well	3.1	4.3	6.2	17.0	2.8	3.2	21.5	7.4
III	River	0.61	4.0	3.1	1.1	1.3	5.3	1.4	0.6
IV	Channel	0.28	2.8	0.2	0.7	2.2	0.3	0.5	0.6
V	Well	0.35	1.4	0.5	1.5	2.3	0.3	0.9	1.5
Vg	*	0.38	1.8	0.5	1.5	2.3	0.7	0.9	1.4

* Water V with ammendment of 35 g. of gypsum per cubic meter of water, just enough to eliminate the excess of bicarbonates over Ca+Mg

LIST OF FIGURES



(Moisture stress=-(M+O); M,O:Matric and Osmotic potentials)



I (mm/hour)
IC, ETC (mm)
HOURS
DAYS
NON SODIC (I)
SODIC (I)
CUM.POT.ET.(ETC)
NON SODIC (IC)
SODIC (IC)

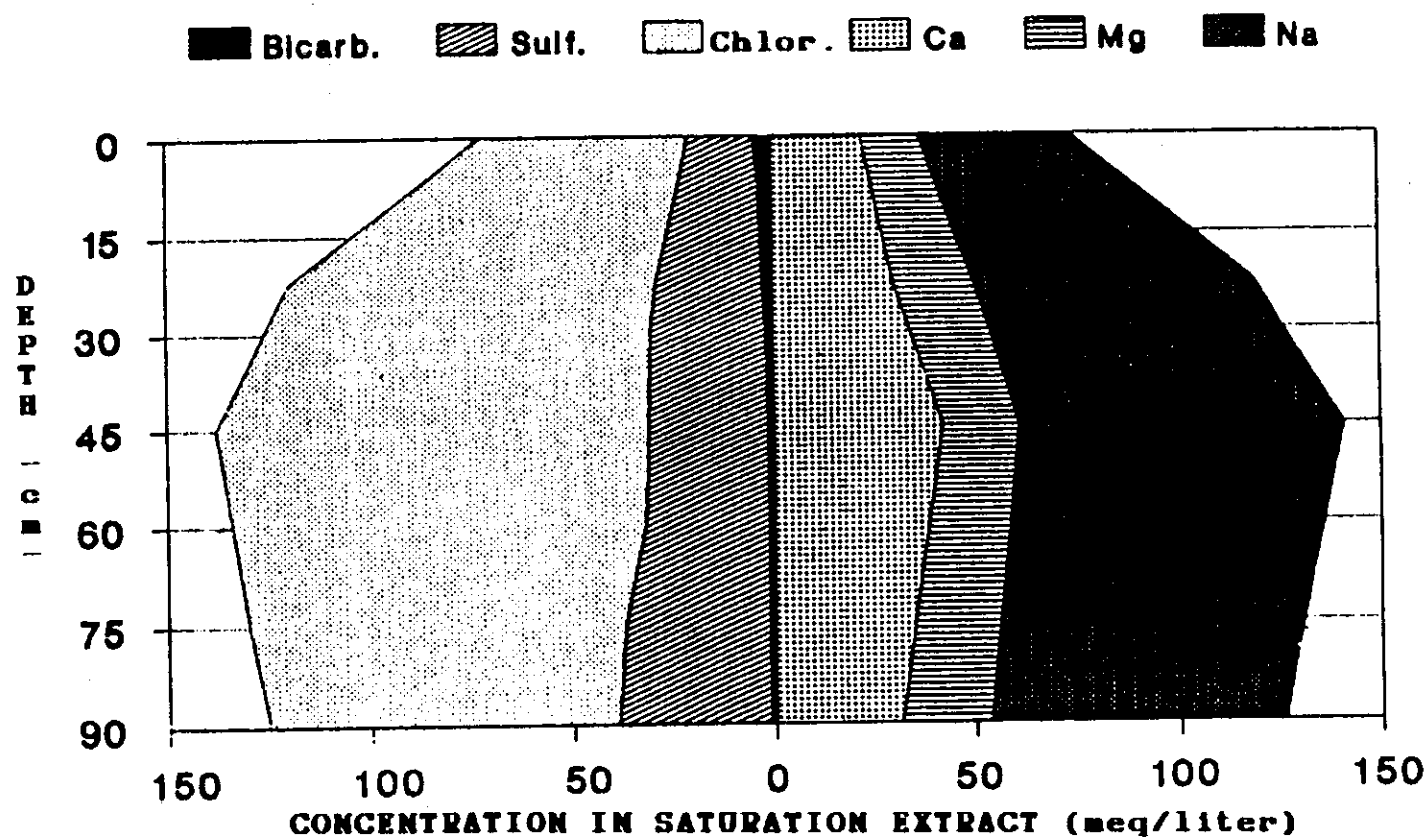
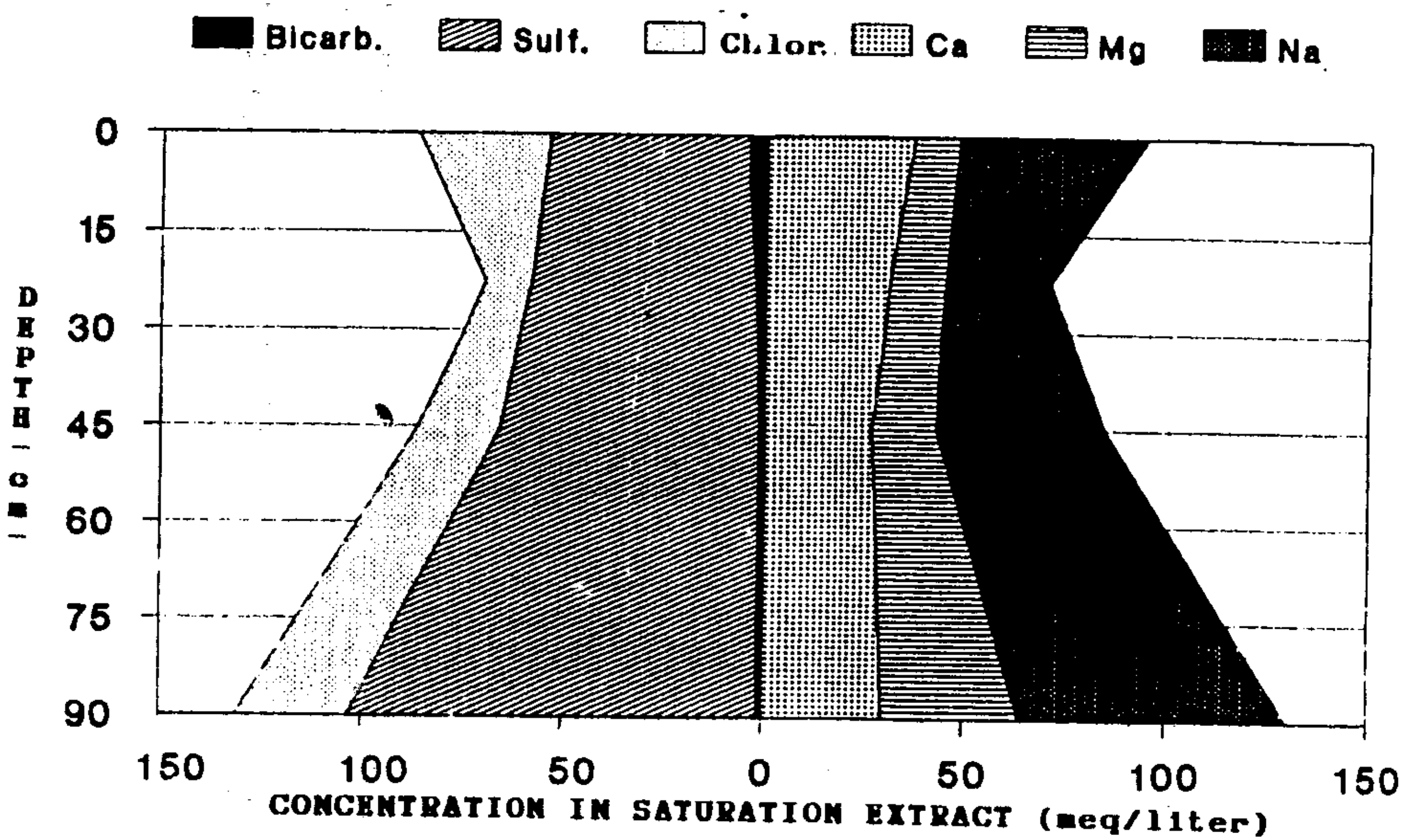

Bicarb.
Sulf.
Chlor.
Ca
Mg
Na
DEPTH (cm)
0
15
30
45
60
75
90
150
100
50
0
50
100
150
CONCENTRATION IN SATURATION EXTRACT (meq/liter)

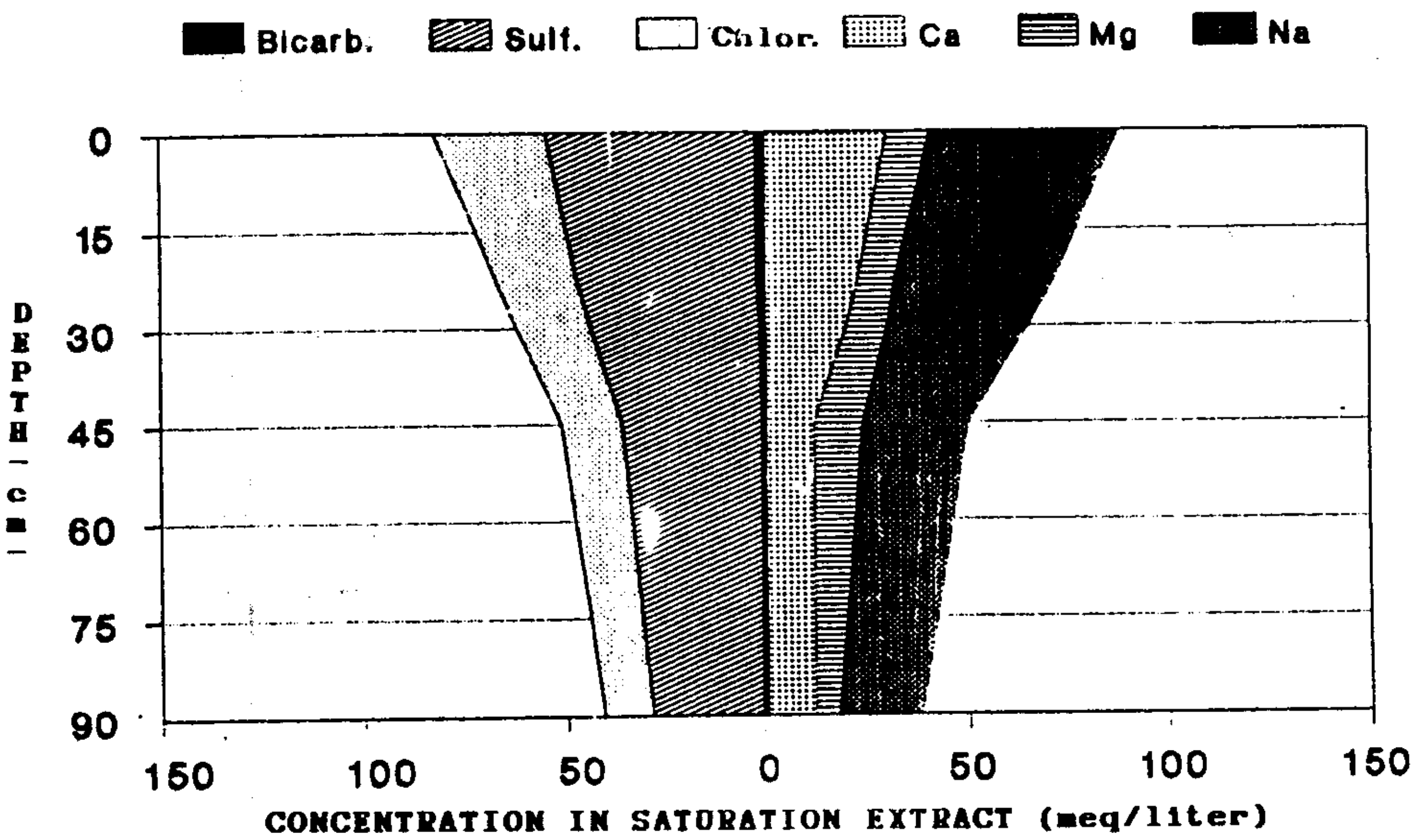
Fig. 3a

21



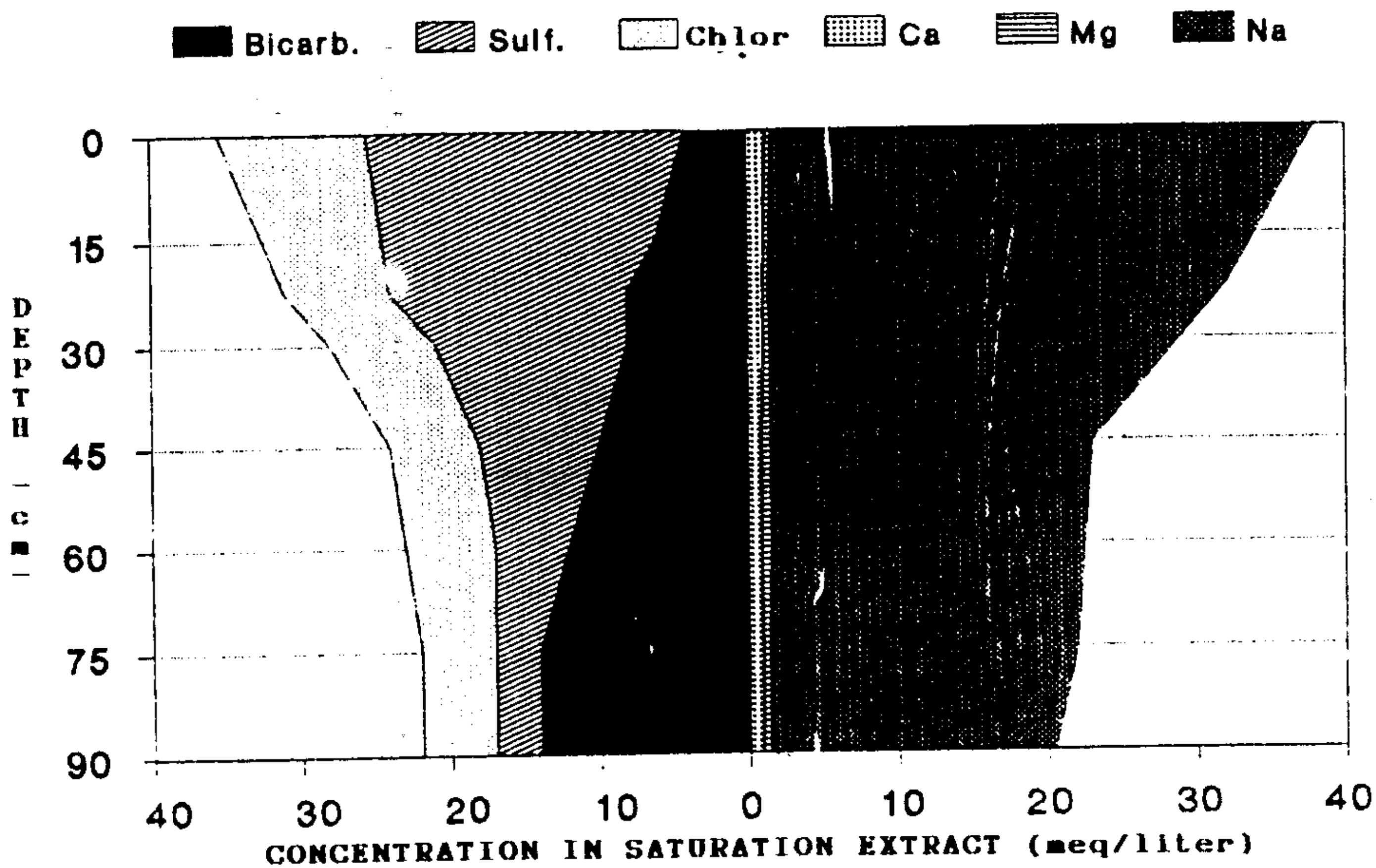
Bicarb.
Sulf.
Chlor.
Ca
Mg
Na
0
15
30
45
60
75
90
DEPTH - cm -
150
100
50
0
50
100
150
CONCENTRATION IN SATURATION EXTRACT (meq/liter)

3C



Bicarb.
Sulf.
Chlor.
Ca
Mg
Na
DEPTH - cm -
0
15
30
45
60
75
90
150
100
50
0
50
100
150
CONCENTRATION IN SATURATION EXTRACT (meq/liter)

T



Bicarb.
Sulf.
Chlor
Ca
Mg
Na
0
15
30
45
60
75
90
DEPTH cm
40
30
20
10
0
10
20
30
40
CONCENTRATION IN SATURATION EXTRACT (meq/liter)

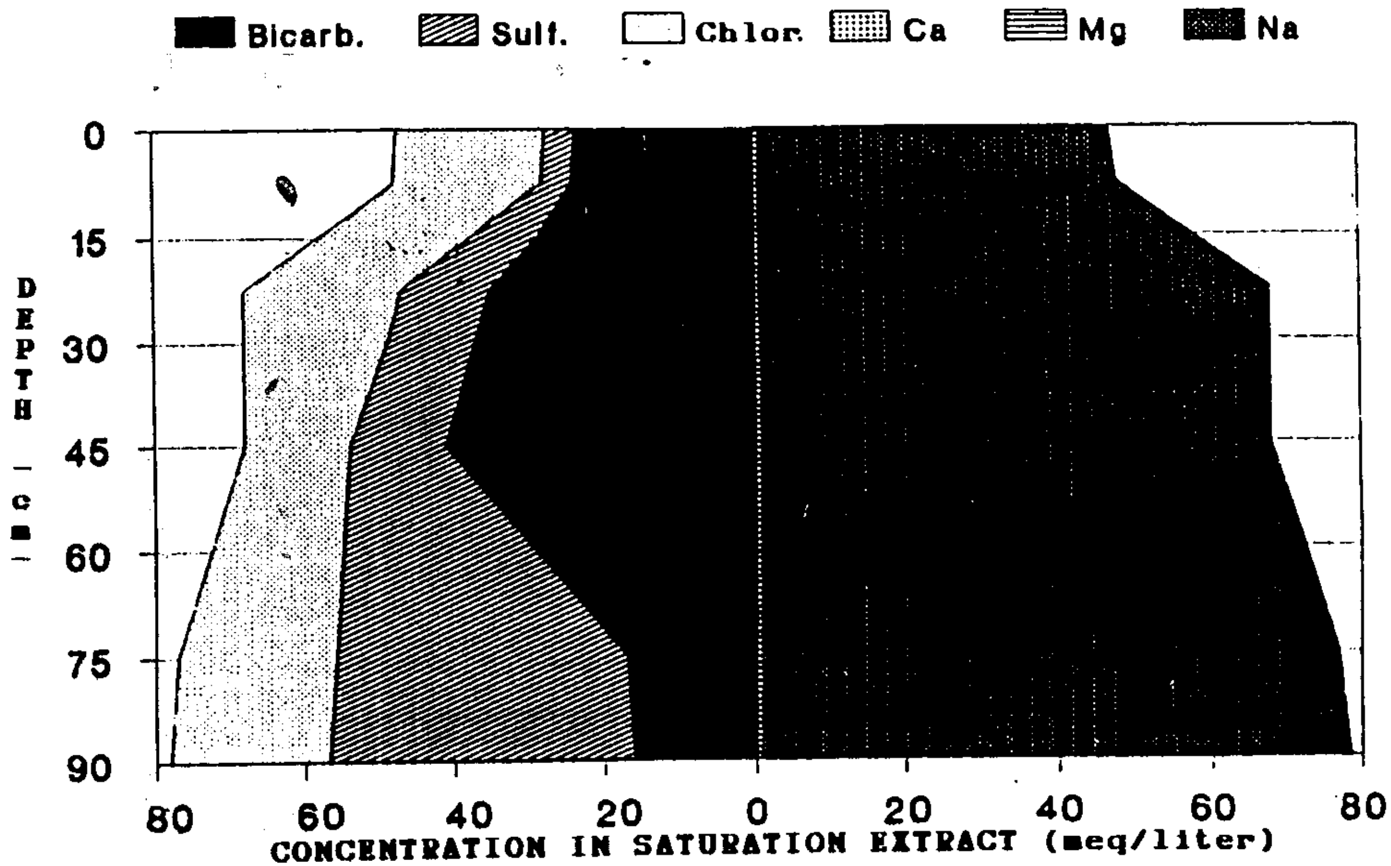

Bicarb.
Sulf.
Chlor.
Ca
Mg
Na
DEPTH – cm –
0
15
30
45
60
75
90
80
60
40
20
0
20
40
60
80
CONCENTRATION IN SATURATION EXTRACT (meq/liter)

Fig. 30

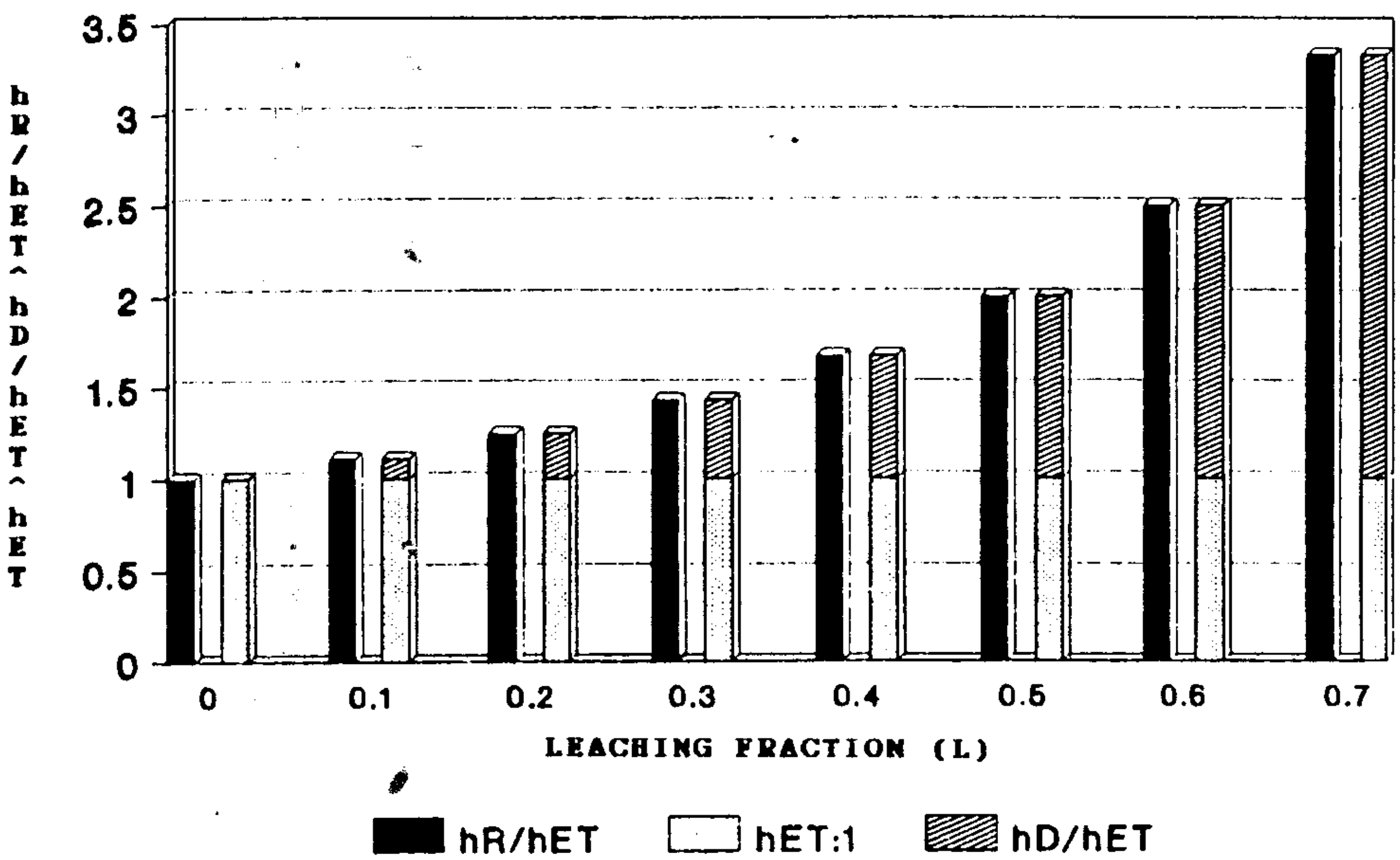
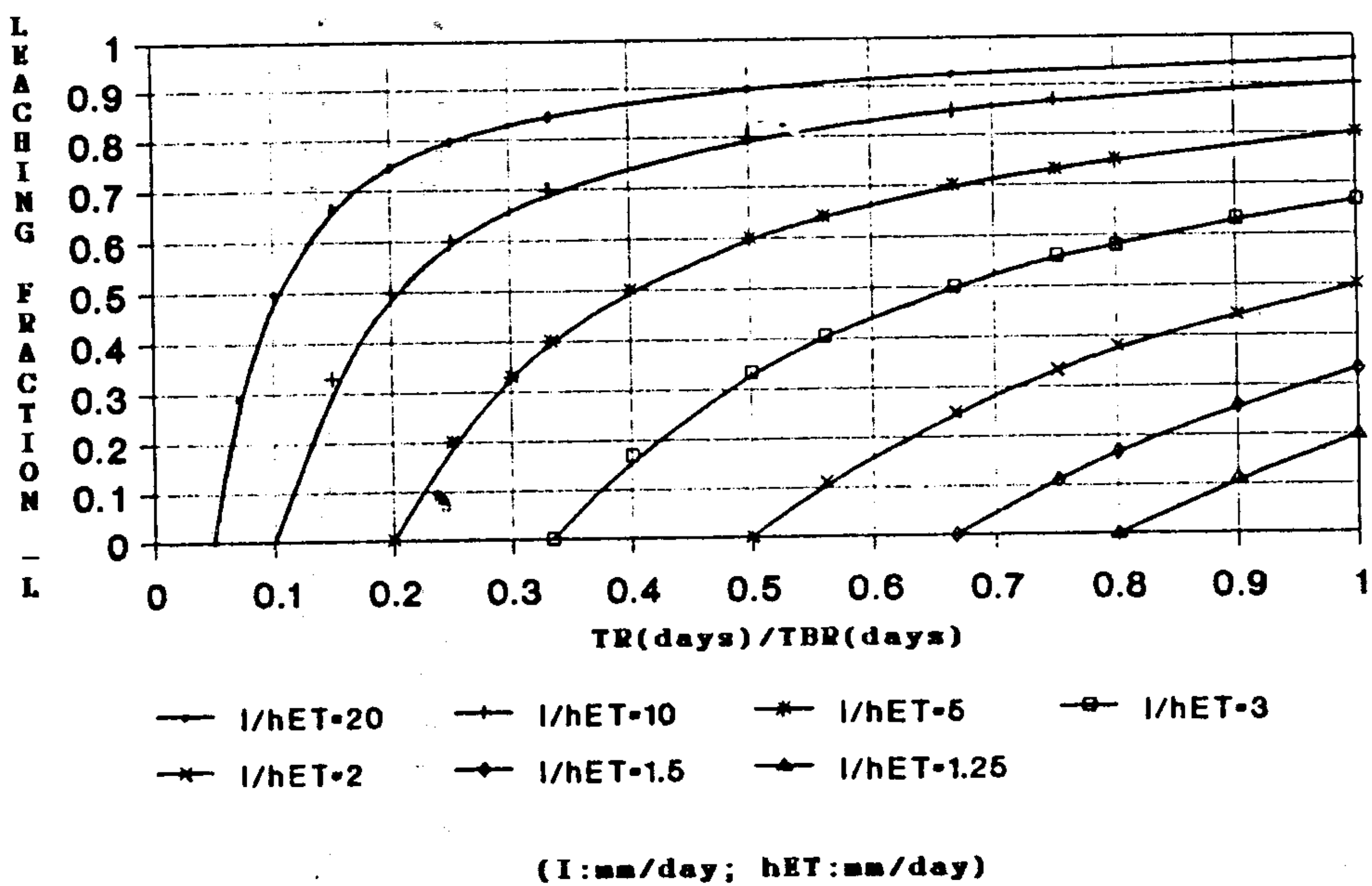
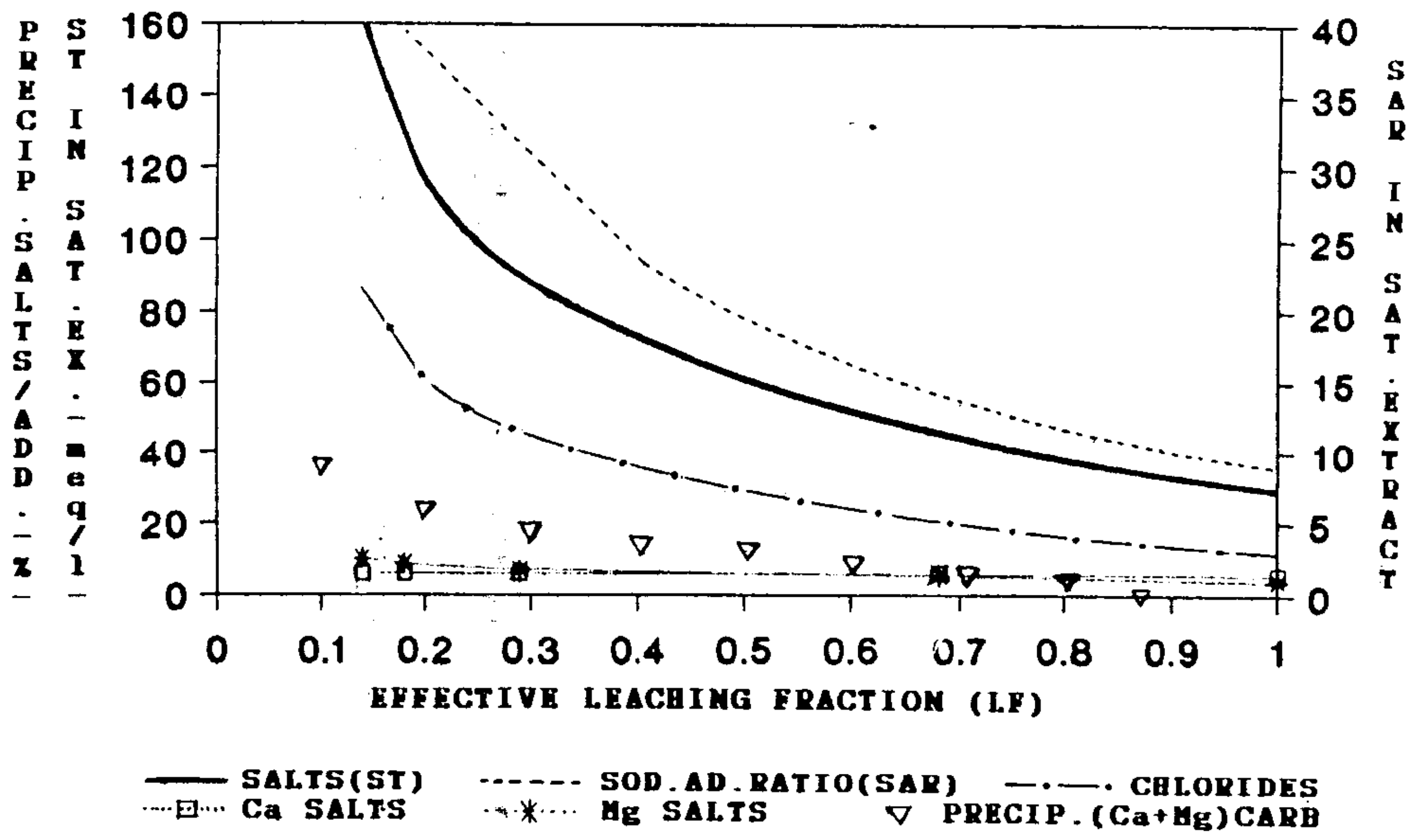
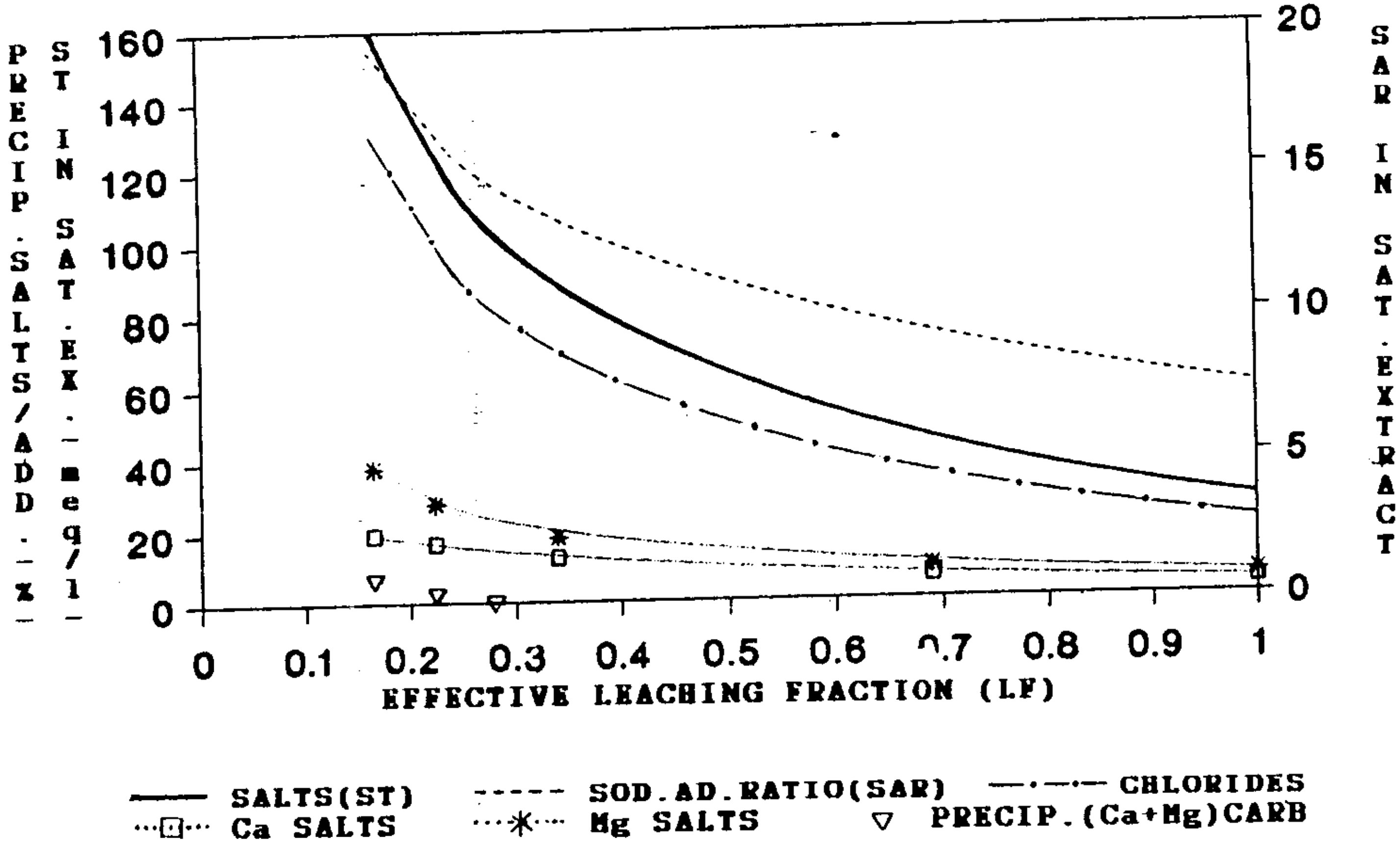

hR/hET, hD/hET, hET
3.5
3
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
LEACHING FRACTION (L)
hR/hET
hET:1
hD/hET

Fig. 4


LEACHING FRACTION _ L
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
TR(days)/TBR(days)
I/hET=20
I/hET=10
I/hET=5
I/hET=3
I/hET=2
I/hET=1.5
I/hET=1.25
(I:mm/day; hET:mm/day)



PRECIP.SALTS/ADD.-%
ST IN SAT.EX.-meq/l
SAR IN SAT.EXTRACT
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EFFECTIVE LEACHING FRACTION (LF)
SALTS(ST)
SOD.AD.RATIO(SAR)
CHLORIDES
Ca SALTS
Mg SALTS
PRECIP.(Ca+Mg)CARB


PRECIP.SALTS/ADD.-%
ST IN SAT.EX.-meq/l
160
140
120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EFFECTIVE LEACHING FRACTION (LF)
20
15
10
5
0
SAR IN SAT.EXTRACT
SALTS(ST)
SOD.AD.RATIO(SAR)
CHLORIDES
Ca SALTS
Mg SALTS
PRECIP.(Ca+Mg)CARB

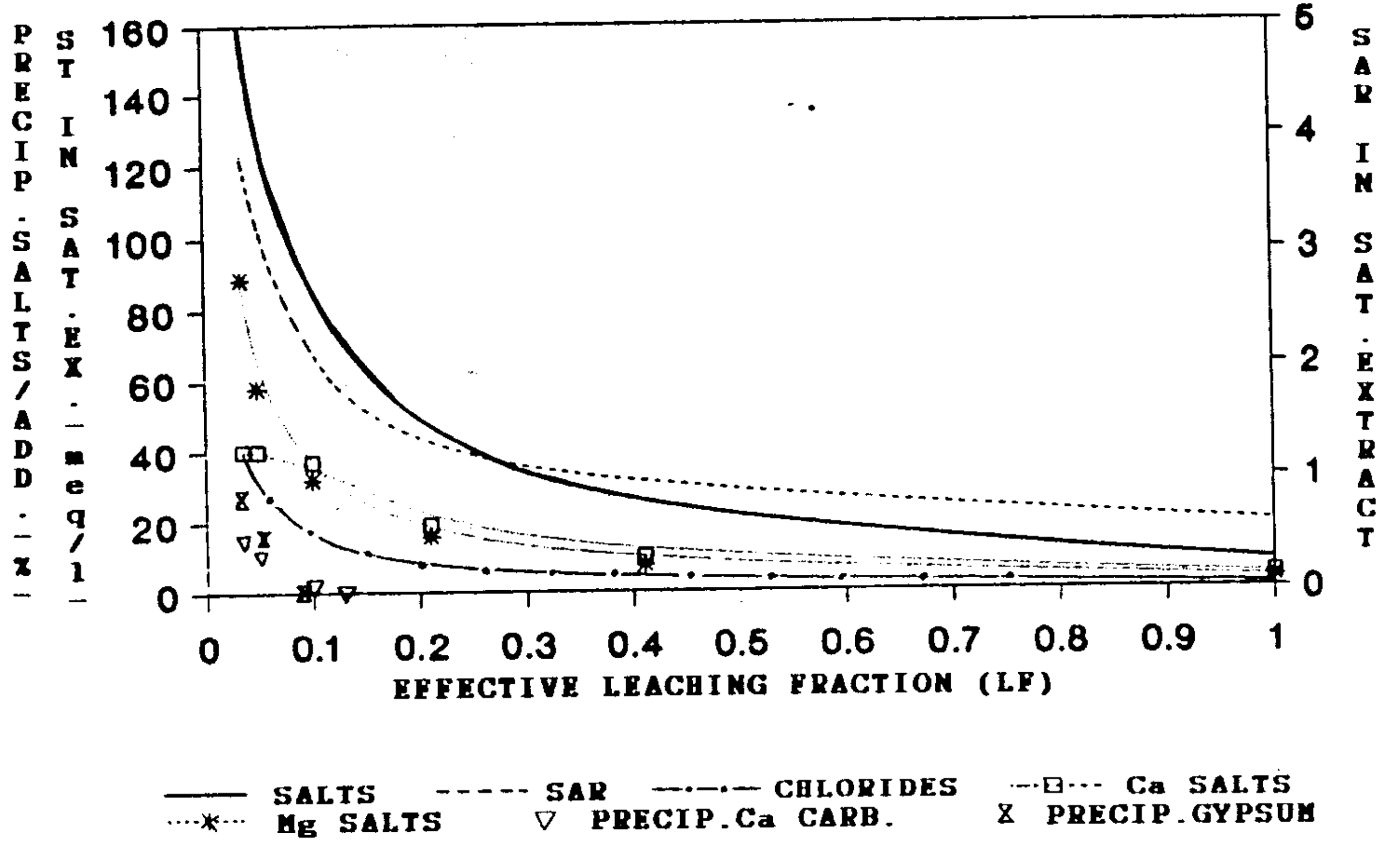

PRECIP.SALTS/ADD.-%
ST IN SAT.EX.-meq/l
160
140
120
100
80
60
40
20
0
SAR IN SAT.EXTRACT
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EFFECTIVE LEACHING FRACTION (LF)
SALTS
SAR
CHLORIDES
Ca SALTS
Mg SALTS
PRECIP.Ca CARB.
PRECIP.GYPSUM

Fig. 6c

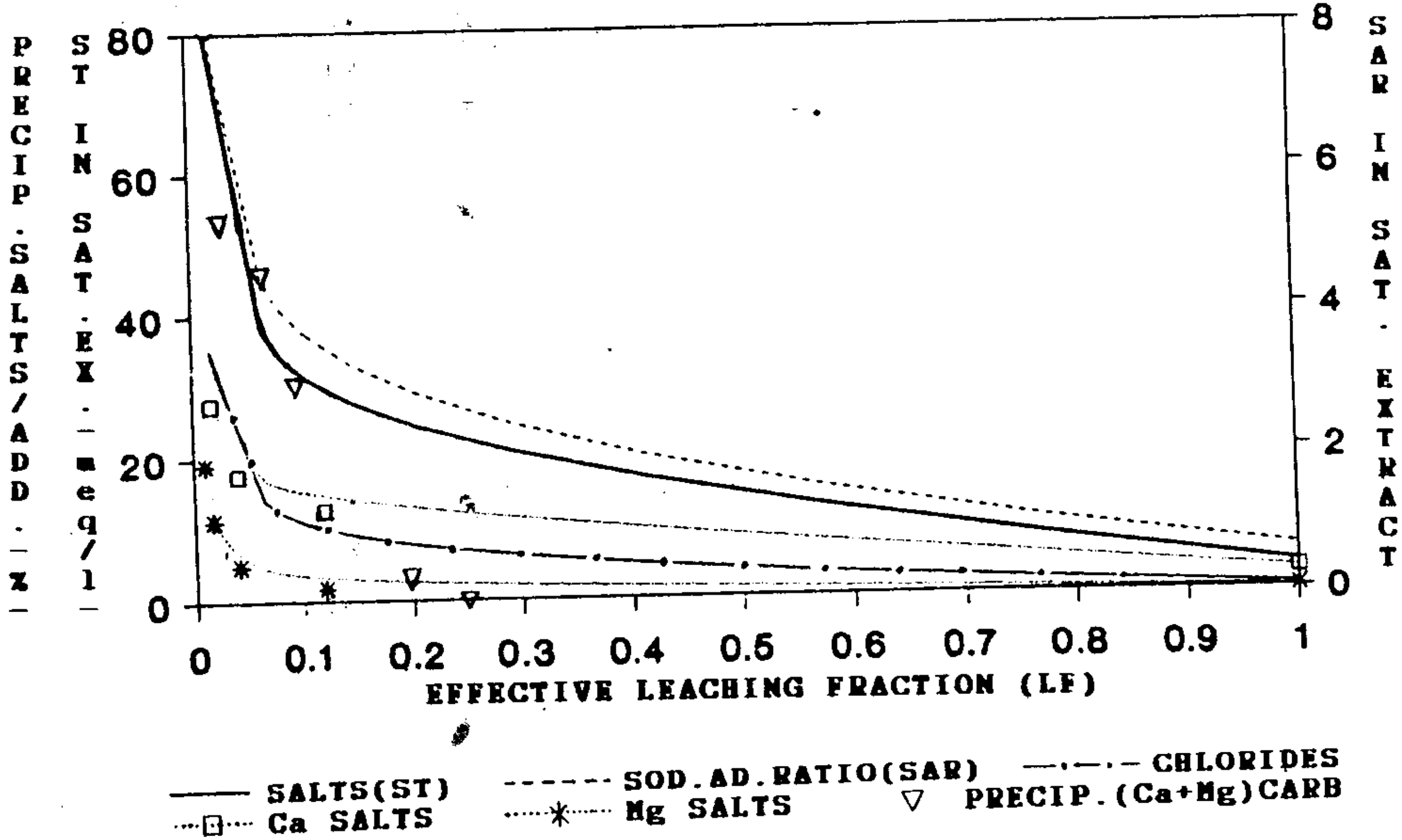

PRECIP.SALTS/ADD.-%
ST IN SAT.EX.-meq/l
SAR IN SAT. EXTRACT
80
60
40
20
0
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EFFECTIVE LEACHING FRACTION (LF)
SALTS(ST)
Ca SALTS
SOD.AD.RATIO(SAR)
Mg SALTS
CHLORIDES
PRECIP.(Ca+Mg)CARB

Fig. 6d

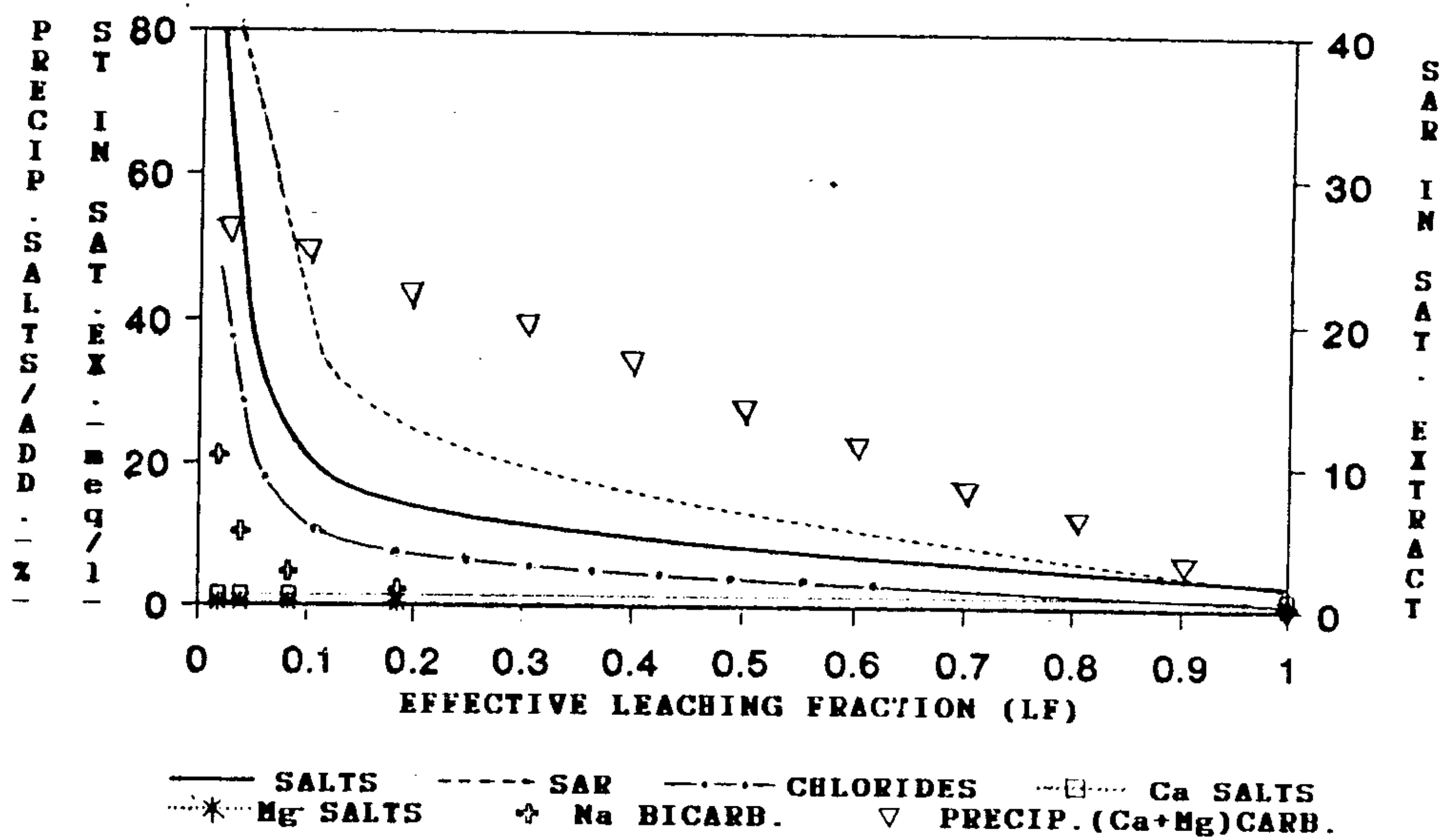
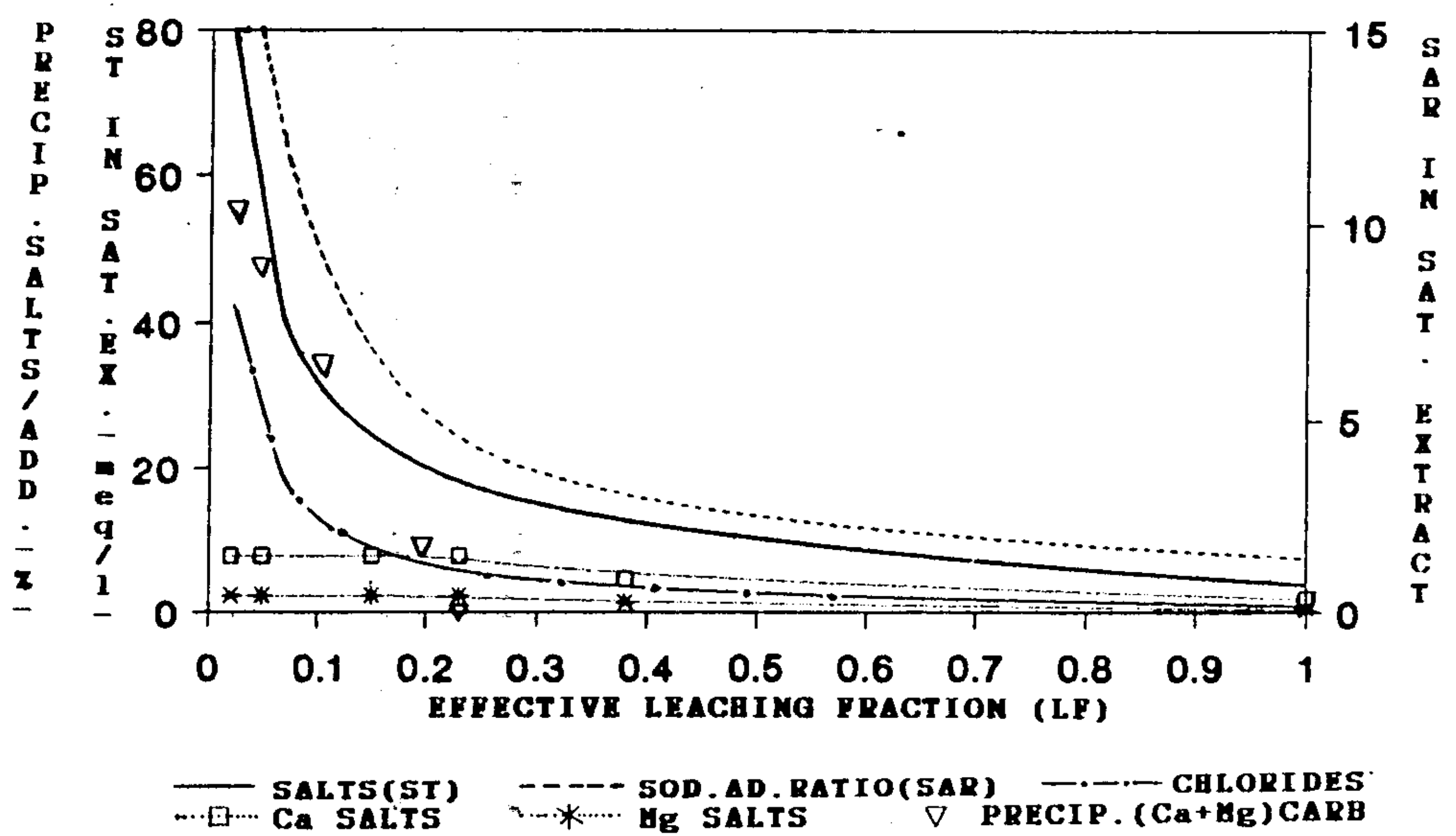

PRECIP. SALTS/ADD. - %
ST IN SAT. EX. - meq/l
SAR IN SAT. EXTRACT
80
60
40
20
0
40
30
20
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
EFFECTIVE LEACHING FRACTION (LF)
SALTS
SAR
CHLORIDES
Ca SALTS
Mg SALTS
Na BICARB.
PRECIP. (Ca+Mg) CARB.

Fig. 6e


PRECIP.SALTS/ADD.-%
ST IN SAT.EX.-meq/l
80
60
40
20
0
15
10
5
0
SAR IN SAT. EXTRACT
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
EFFECTIVE LEACHING FRACTION (LF)
SALTS(ST)
SOD.AD.RATIO(SAR)
CHLORIDES
Ca SALTS
Mg SALTS
PRECIP.(Ca+Mg)CARB

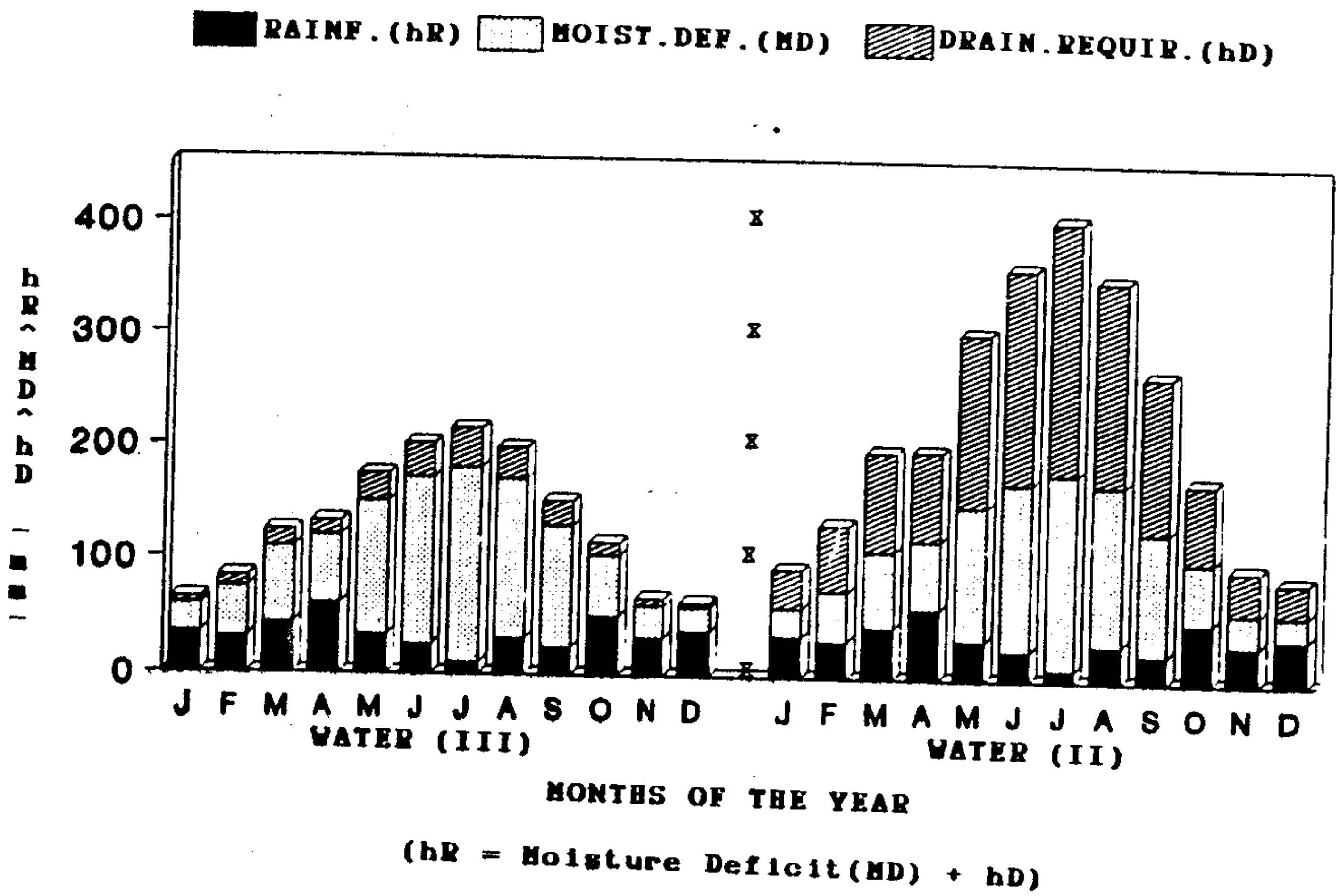

RAINF.(hR) MOIST.DEF.(MD) DRAIN.REQUIR.(hD)
hR^MD^hD (mm)
400
300
200
100
0
J F M A M J J A S O N D
WATER (III)
J F M A M J J A S O N D
WATER (II)
MONTHS OF THE YEAR
(hR = Moisture Deficit(MD) + hD)

Fig. 7