IMPACT OF RECLAMATION OF SODIC LAND
ON
GROUND WATER QUALITY

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
IRRIGATION WATER MANAGEMENT

By

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CANDIDATES'S DECLARATION

I hereby declare that the dissertation entitled **"IMPACT OF RECLAMATION OF SODIC LAND ON GROUND WATER QUALITY"** is being submitted by me in partial fulfillment of requirement for the award of degree of **"Master of Technology** in **IRRIGATION WATER MANAGEMENT"** submitted in the department of Water Resources Development and Management, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during the period from July, 2004 to June, 2005 under the guidance of **Dr. G. C. Mishra**, Professor, Water Resources Development and Management Department, Indian Institute of Technology, Roorkee.

The matter embodied in the dissertation has not been submitted by me for the award of any other degree.

(C.L. Gupta)

Roorkee, Dated: June 29, 2005

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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CHAPTER-3 LEACHING OF SALTS IN SODIC LAND

SYNOPSIS

A mathematical model using the relationship of rate of transfer of salt from immobile water to mobile water with the concentration difference between the two regions is developed to predict the salt concentration with time applying infiltration of water. Using Green and Ampt equation an expression is derived showing relationship between time and depth of saturation front in the root zone. This relationship is utilized in the mathematical model.

A certain depth of water is applied on the surface of soil assuming it to be at field capacity and simulation is made. The result shows that after onset of infiltration the concentration in the mobile water is increasing and that in immobile water is decreasing. When left for ten days to take exchange, both are converging to a middle value of the initial concentration. Again applying the same depth of water, concentration in both regions are decreasing. Finally we get the concentration well within the permissible limit.

This model is believed to be more efficient for prediction of the variation in salt cincentration with time from the onset of infiltration.

CHAPTER-1

INTRODUCTION

1.1 DESCRIPTION OF PROBLEM

Salts are the bane of both irrigated agriculture and of civilization that are based on irrigated agriculture, particularly if irrigation water and soil drainage are improperly managed. During the course of human history, thriving civilizations whose existance was based on irrigated agriculture have declined or disappeared, in part due to poor irrigation water management practices. For example, the Harappa civilization in the Indus Plain region of India and Pakistan, the inhabitants of the lower Viru Valley in Peru, and the Hohokam Indians in the Salt River region of Arizona have all succumbed to the degrative effects of soil salinization. However, no where in the recorded history of man, the influence of poor water management is more graphically illustrated than in the desert region of the Middle East occupied by present day Iraq. The land between the Tigris and Euphrates Rivers in southern Iraq, known as the "cradle of civilization", ancient Mesopotania ("the land between the rivers"), or Sumer in ancient times, is now desolate and barren, consisting of salt-encrusted soils. At one time (beginning over 6000 years ago) this region, a desert then as it is now, consisted of lush and productive fields of cereal grains, palm groves, and forage for livestock. The Sumerians colonized and transformed the desert by diverting water from the Euphrates River through a series of canals. They introduced irrigated agriculture to the region. The irrigetion practices that were begun by the Sumerians continued under subsequent dynasties, such as the Akkadians and the Assyrians.

The center of civilization and power in Mesopotamia gradually shifted northwards as dynasties changed. Hillel (1992) points out that the decline of civilization in Sumer, and the northward migration of civilization, could be related to the decline of agriculture in the region. The salinization and sterilization of the soil in southern Mesopotamia resulted from a lack of adequate drainage and the introduction of salts in irrigated waters. The Euphrates was a slat-laden river during ancient times. As the river neared its lower reaches, the sediment settled onto the riverbed and banks, elivating the riverbed to the surrounding plains. As a result, water table levels in the region rose. Irrigation further contributed to the elevated level of the water table. It is estimated that the Euphrates loses approximately half its volume through evaporation (which concentrates salts) and seepage between its source and the Mesopotamia plain. Thus, the irrigation waters contained dissolved salts, which added to the salts released from the soil solids by mineral weathering. Although irrigation would move salts into the groundwater, the salts remained in close proximity to the surface, as the water table was near the soil surface and the groundwater did not have adequate natural flow out of the region. Further, when the water table became shallow, capillary rise moved salts up to the soil surface. Because drainage was inadequate and salts were added with continued irrigation, they accumulated at the surface soil and in the groundwater. With time, this process degraded the soil and destroyed the region's irrigation-based agriculture.

Excess salts in surface soils is a condition common in arid and semiarid regions where evaporation exceeds precipitation. Poor irrigation water management exacerbates the problem of salinity. Indeed, irrigation will inevitably lead the salinization of soils if proper water management practices are not employed. The impact that excess salt have on soil's physical and chemical characteristics depends on the type of salt present in soil or irrigation water. Excessive concentration of Na (sodicity) can promote high soil pH, slaking of aggregates, and swelling and dispersion of soil clays. These physical conditions degrade soil structure and impede water and root penetration. Current data indicate that poor irrigation practices result in the loss of an estimated 10 million hectares of arable land every year as a result of soil salinization or sodification. It is estimated that approximately 7 x 10^9 ha of the Earth's land surface is arable, with 1.5 x 10^9 ha cultivated (Massoud, 1981). Szabolcs (1989) estimates that 351.2 x 10^6 ha of the Earth's cultivated land surface is saline and 581.0 x 10^6 ha is sodic. Thus, 5% of arable land and 23% of the word's cultivated lands are saline; 8% of arable and 39% of cultivated are sodic.

As far as India is concerned, sodic land is the basic problem faced by a large number of small & marginal farmers throughout the country. Statistics reveal that U.P. alone has 168417 hectare of sodic land out of 2981907 hectares of total land. Economic surveys conducted by the Govt.of India revealed that cumulative irrigated land stood at 85 million hectares. As such the nation is faced with an unprecedented problem of sodic land which continues to engulf the cultivable lands due to various pollution factors. Therefore, belated efforts have now been made in this direction to check the degradation of the soil & increase the agriculture productivity vis-a-vis farmers' economy. Hitherto, efforts have been concentrated on the use of chemical methods to reclaimate the sodic land which includes the use of Pyrites, Gypsum etc. The sustainability of the reclaimation of sodic land using chemical methods have serious limitations & are increasingly being questioned!

The contribution of sodic land in the total waste land is very high in India. In U.P. alone the available figures reveals that out of 2981907 hectares of total land, 168417 hectare is identified as sodic land. The situation in other states is more or less the same but for the geographical variables. Most soil degradation is caused by human activities like overgrazing, deforestation, poor land management, over exploitation, discharge of waste water, garbage dumping; the soil erosion, decline in biological degradation, hydrologic degradation etc. are the well known consequences of waste land formation. Silty loam to loam soils have been reported to contain higher amounts of soluble salts. The ECe ranges from 9 to 29 ds/m & the pH is as high as 10. Carbonate & bicarbonate are the dominant anions with chlorides & sulphates in major amounts. The poorly drained soil of low permeability have a high calicic value at a depth of about 1 meter. They have low amounts of available N & P & medium amounts of available K.

Survey of sodic land in Haryana using multiband FCC land sat imageries in 1:250,000 scale have been conducted. Multidata imageries over the past 10 years showed that the alkali affected area in Haryana has shrunk considerably but 16,000 hectares remain unreclaimed. Various institutions in different states have focused attention on the reclaimation of sodic land and majority of them have predominatly confined their attempts to the use of chemical methods. A brief account of the past experience in handling the sodic land is detailed below:-

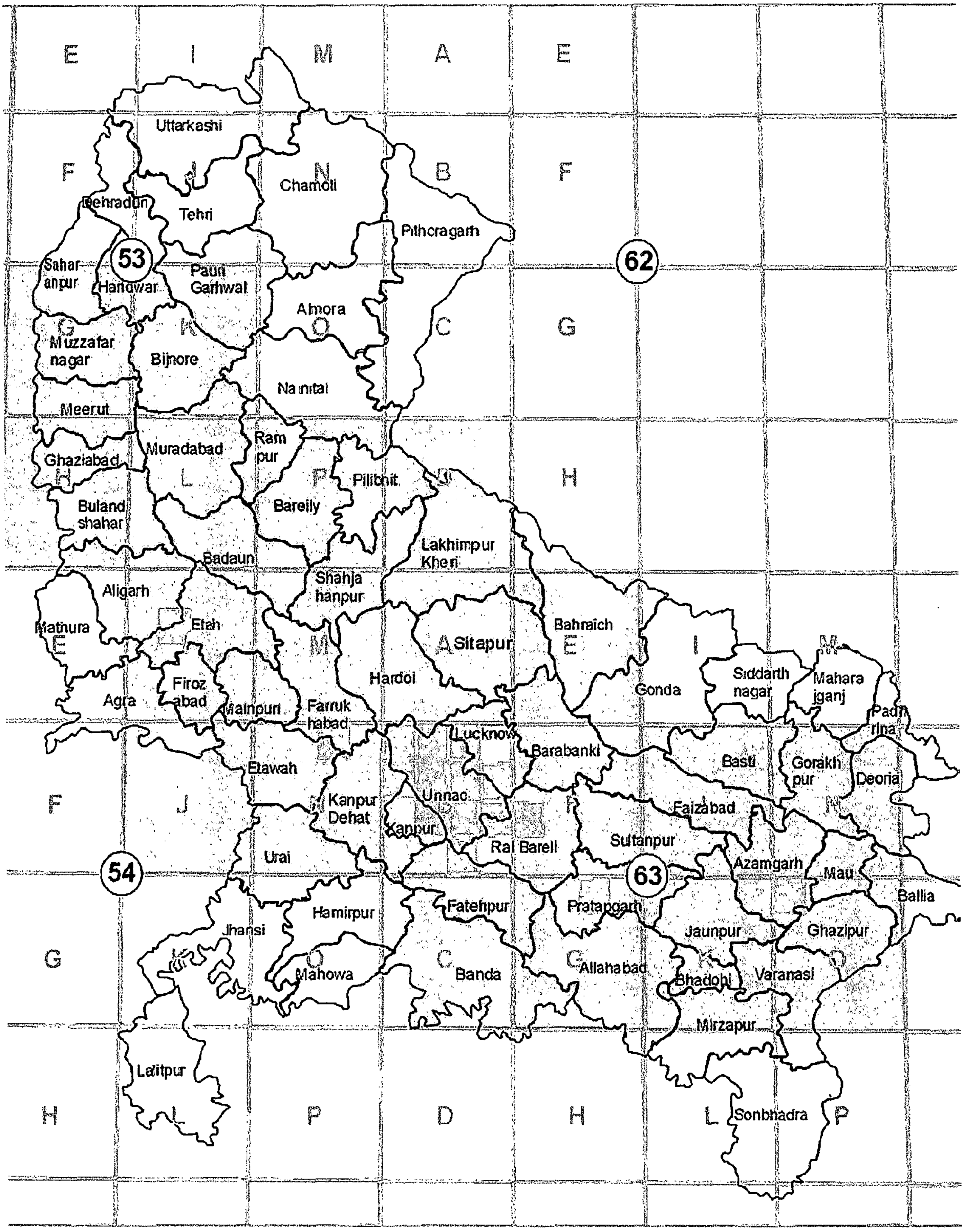
- A single dose of 75% of the requirement of Gypsum in the sodic calcarious clay soil increased the yield of wheat (2.59 tonnes/hectare) & rice on a similar soil at Indore. The use of Pyrites (alone or in combination with form yard manure ground nut, husk & wheat straw) increased the yield of rice (3.2 tonnes/hactare) & wheat (2.9 tonnes/hactare).
- Raising claster bean for three successive years resulted in an increase of the mineralised & organic N fractions of the soil consequently pearl millet raised on such a soil gave higher yield.
- High doses of N & P reduced the adverse effect of irrigating wheat with saline water, both soil sensitive varieties gave higher yields with salinity stress ,80 kg N,& 90 kg P/hectare than with no salinity stress & no N & P.

In U.P. Sodic Land Reclaimation Project is carried out. REMOTE SENSIMG APPLICATION CENTRE, U.P. LUCKNOW is doing the assessment of the environmental impacts of Sodic Land Reclaimation on ground water quality. The monitoring is being carried out in 66 project sites of seventeen U.P. Sodic Land Reclaimation Project districts, viz. Aligarh, Auraiya, Allahabad, Etah, Etawah, Fatehpur, Hardoi, Hathras, Mainpuri, Pratapgarh, Raebareli and Sultanpur since 1999 and since pre monsoon 2002 in newly added districts viz. Azamgarh, Bulandshahar, Jaunpur, Kanpur and Unnao. The project districts fall in the canal command of Sharda, Sharda Sahayak, Upper Ganga, Lower Ganga and Ram Ganga.

The quality of ground water in the study area is generally alkaline, with pH varying from 8.0 to 8.9. The temporal variation in ground water quality shows slight increase in cations and anions in 1st and 2nd years of reclaimation (2000 and 2001, respectively) but not beyond permissible limit.

1.3 PURPOSE AND OBJECTIVES

The broad objective of this thesis is to find a solution for prediction of salt concentration in the sodic soil. It is a fact that desodification followed by leaching of displaced sodium detriorates the ground water quality while it is required for improving the food production. Hence a proper management is mnst for maintaining the groundwater quality while reclaiming the land.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CHAPTER-2

REVIEW OF LITERATURE

2.1 ORIGIN AND NATURE OF SALINE AND ALKALI (SODIC) SOILS

The soils under consideration owe their distinctive character to the fact that they contain excessive concentrations of either soluble salts or exchangeable sodium, or both. For agricultural purposes, such soils are regarded as a class of problem soils that requires special remedial measures and management practices. Soluble salts produce harmful effects to plants by increasing the salt content of the soil solution and by increasing the degree of saturation of the exchange materials in the soil with exchangeable sodium. The latter effect occurs when the soluble constituents consist largely of sodium salts and is of a more permanent nature than the salt content of the soil solution, since exchangeable sodium usually persists after the soluble salts are removed.

In discussing these problem soils it is convenient to use terms that refer specifically to the two principal causes of the problem. "Saline soil," as used in this handbook, refers to a soil that contains sufficient soluble salts to impair its productivity. Similarly, alkali soils can be defined in terms of productivity as influenced by exchangeable sodium. In accordance with this usage, alkali soils may or may not contain excess soluble salts. Probably the most common problem involves soils that contain an excess of both soluble salts and exchangeable sodium, and these soils will be referred to as saline-alkali soils.

The salt content of soils above which plant growth is affected depends upon several factors, among which are the texture of soil, the distribution of salt in the profile, the composition of the salt, and the species of plant.

The decision regarding what level of exchangeable sodium in the soil constitutes an excessive degree of saturation is complicated by the fact that there is no sharp change in the properties of the soil as the degree of saturation with exchangeable sodium is increased. In the past an exchangeable-sodium-percentage of 15 has been used at the Laboratory as a boundary limit between nonalkali and alkali soils. Insufficient data and experience are available to justify a change, but this limit must be regarded as somewhat arbitrary and tentative. In some cases, for example, 2 or 3 milliequivalents of exchangeable sodium per 100 gm. of soil has equal or even greater usefulness as a critical limit. It has been observed in several instances that alkali soils high in exchangeable potassium have better physical properties and are more readily reclaimable than other alkali soils containing similar amounts of exchangeable sodium but low amounts of exchangeable potassium.

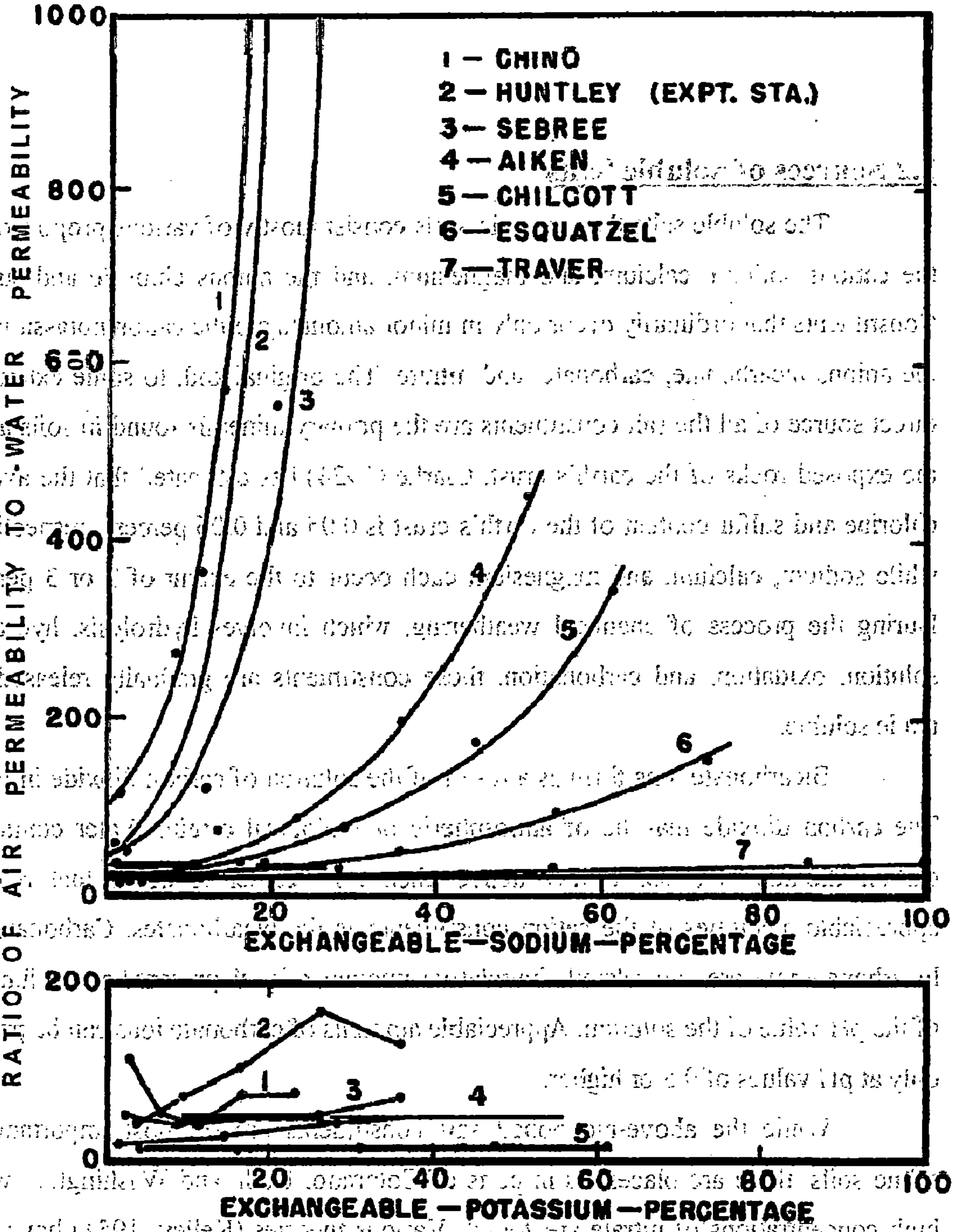


FIGURE 1.—Relative effect of exchangeable sodium and exchangeable potassium on the ratio of the air permeability to the water permeability of soils.

2.2 Sources of Soluble Salts

The soluble salts that occur in soils consist mostly of various proportions of the cations sodium, calcium, and magnesium, and the anions chloride and sulfate. Constituents that ordinarily occur only in minor amounts are the cation potassium and the anions bicarbonate, carbonate, and nitrate. The original and, to some extent, the direct source of all the salt constituents are the primary minerals found in soils and in the exposed rocks of the earth's crust. Clarke (1924) has estimated that the average chlorine and sulfur content of the earth's crust is 0.05 and 0.06 percent, respectively, while sodium, calcium, and magnesium each occur to the extent of 2 or 3 percent. During the process of chemical weathering, which involves hydrolysis, hydration, solution, oxidation, and carbonation, these constituents are gradually released and made soluble.

Bicarbonate ions form as a result of the solution of carbon dioxide in water. The carbon dioxide may be of atmospheric or biological origin. Water containing carbon dioxide is a particularly active chemical weathering agent that releases appreciable quantities of the cation constituents as the bicarbonates. Carbonate and bicarbonate ions are interrelated, the relative amounts of each present being a function of the pH value of the solution. Appreciable amounts of carbonate ions can be present only at pH values of 9.5 or higher.

While the above-mentioned salt constituents are of most importance in saline soils, there are places, as in parts of Colorado, Utah, and Washington, where high concentrations of nitrate are found. Various theories (Kelley, 1951) have been proposed to explain the origin of excessive nitrate salts in soils. Boron, owing to its marked toxicity to plants when present even in low concentrations, also deserves mention (Eaton and Wilcox, 1939). The principal source of this element is the mineral tourmaline, which is a rather widespread but minor constituent of primary rocks.

Although weathering of primary minerals is the indirect source of nearly all soluble salts, there are probably few instances where sufficient salts have accumulated in place from this source alone to form a saline soil. Saline soils usually occur in areas that receive salts from other locations, and water is the primary carrier.

The ocean may be the source of salts as in soils where the parent material consists of marine deposits that were laid down during earlier geologic periods and have since been uplifted. The Mancos shales occurring in Colorado, Wyoming, and Utah are typical examples of saline marine deposits. The ocean is also the source of the salts in low-lying soils along the margin of seacoasts. Sometimes salt is moved inland through the transportation of spray by winds and is called cyclic salt (Teakle, 1937). More commonly, however, the direct source of salts is surface and ground waters. All of these waters contain dissolved salts, the concentration depending upon the salt content of the soil and geologic materials with which the water has been in contact. Waters act as sources of salts when used for irrigation. They may also add salts to soils under natural conditions, as when they flood low-lying land or when ground water rises close to the soil surface.

2.3 Salinization of Soils

Saline soils occur for the most part in regions of arid or semiarid climate. Under humid conditions the soluble salts originally present in soil materials and those formed by the weathering of minerals generally are carried downward into the ground water and are transported ultimately by streams to the oceans. Saline soils are, therefore, practically nonexistent in humid regions, except when the soil has been subjected to sea water in river deltas and other low-lying lands near the sea. In arid regions leaching and transportation of soluble salts to the ocean is not so complete as in humid regions. Leaching is usually local in nature, and soluble salts may not be transported far. This occurs not only because there is less rainfall available to leach and transport the salts but also because of the high evaporation rates characteristic of arid climates, which tend further to concentrate the salts in soils and in surface waters.

Restricted drainage is a factor that usually contributes to the salinization of soils and may involve the presence of a high ground-water table or low permeability of the soil. The high ground-water table is often related to topography. Owing to the low rainfall in arid regions, surface drainageways may be poorly developed. As a consequence, there are drainage basins that have no outlet to permanent streams. The drainage of salt-bearing waters away from the higher lands of the basin may raise the ground-water level to the soil surface on the lower lands, may cause temporary flooding, or may form permanent salty lakes. Under such conditions upward movement of saline ground water or evaporation of surface water results in the formation of saline soil. The extent of saline areas thus formed may vary from a few acres to hundreds of square miles. Many of the saline soils in the Great Basin were formed in this manner. Similar areas occur throughout the Western States. They are often referred to as playas or dry lakes.

Low permeability of the soil causes poor drainage by impeding the downward movement of water. Low permeability may be the result of an unfavorable soil texture or structure or the presence of indurated layers.

The salinity problem of principal economic importance arises when previously nonsaline soil becomes saline as the result of irrigation. Such soils are often located in valleys adjacent to streams, and, because of the ease with which they can be irrigated, the more level areas are usually selected for cultivation. While such soils may be well drained and nonsaline under natural conditions, the drainage may not be adequate for irrigation. When bringing new lands under irrigation, farmers have frequently failed to recognize the need for establishing artificial drains to care for the additional water and soluble salts. As a result, the ground-water table may rise from a considerable depth to within a few feet of the soil surface in a few years. During the early development of irrigation projects, water is frequently plentiful and there is a tendency to use it in excess. This hastens the rise of the water table. Waters used for irrigation may contain from 0.1 to as much as 5 tons of salt per acre-foot of water, and the annual application of water may amount to 5 feet or more. Thus, considerable quantities of soluble salts may be added to irrigated soils over relatively short periods of time. When the water table rises to within 5 or 6 feet of the soil surface, ground water moves upward into the root zone and to the soil surface. Under such conditions, ground water, as well as irrigation water, contributes to the salinization of the soil.

2.4 Accumulation of Exchangeable Sodium in Soils

Soil particles adsorb and retain cations on their surfaces. Cation adsorption occurs as a consequence of the electrical charges at the surface of the soil particles.

While adsorbed cations are combined chemically with the soil particles, they may be replaced by other cations that occur in the soil solution. The reaction whereby a cation in solution replaces an adsorbed cation is called cation exchange. Sodium, calcium, and magnesium cations are always readily exchangeable. Other cations, like potassium and ammonium, may be held at certain positions on the particles in some soils so that they are exchanged with great difficulty and, hence, are said to be fixed.

Cation adsorption, being a surface phenomenon, is identified mainly with the fine silt, clay, and organic matter fractions of soils. Many different kinds of mincrals and organic materials occurring in soils have exchange properties and together are referred to as the exchange complex. The capacity of a soil to adsorb and exchange cations can be measured and expressed in chemical equivalents and is called the cation-exchange-capacity. It is commonly expressed in milliequivalents per 100 gm. of soil. Various chemical and physical factors interact to make the measured value depend somewhat on the method of determination, but, nevertheless, the cation-exchange-capacity is a reasonably definite soil property that has considerable practical significance. In view of the fact that the adsorbed cations can interchange freely with adjacent cations in the soil solution, it is to be expected that the proportion of the various cations on the exchange complex will be related to their concentrations in the soil solution.

Calcium and magnesium are the principal cations found in the soil solution and on the exchange complex of normal soils in arid regions. When excess soluble salts accumulate in these soils, sodium frequently becomes the dominant cation in the soil solution. Thus, sodium may be the predominant cation to which the soil has been subjected, or it may become dominant in the soil solution, owing to the precipitation of calcium and magnesium compounds. As the soil solution becomes concentrated through evaporation or water absorption by plants, the solubility limits of calcium sulfate, calcium carbonate, and magnesium carbonate are often exceeded, in which case they are precipitated with a corresponding increase in the relative proportion of sodium. Under such conditions, a part of the original exchangeable calcium and magnesium is replaced by sodium.

From a practical viewpoint, it is fortunate that the calcium and magnesium cations in the soil solution are more strongly adsorbed by the exchange complex than sodium. At equivalent solution concentrations, the amounts of calcium and magnesium adsorbed are several times that of sodium. In general, half or more of the soluble cations must be sodium before significant amounts are adsorbed by the exchange complex. In some saline soil solutions, however, practically all of the cations are sodium, and in these sodium is the predominant adsorbed cation.

2.5 Characteristics of Saline and Alkali Soils

The term "soil" is used in several senses by agriculturists. In one sense a soil is considered to be a threedimensional piece of landscape having shape, area, and depth (Soil Survey, 1951). The concept of a soil as a profile having depth but not necessarily shape or area is also a common use of the term. In another sense, often used in this handbook, the term is applied to samples representing layers or points in the profile. Saline and alkali soils are defined and diagnosed on the basis of determinations made on soil samples, and the significance of information thus obtained contributes substantially to scientific agriculture. The extension and harmonization of these definitions to the problems and purposes of soil survey and soil classification have not been attempted, because it lies somewhat beyond the scope of the present work.

To facilitate and clarify this discussion, the problem soils under consideration have been separated into three groups : **Saline**, **saline-alkali**, and **nonsaline-alkali** soils. **Saline-alkali**, and **nonsaline-alkali** soils come under **Sodic soils.**

2.5.1 Saline Soils

Saline is used in connection with soils for which the conductivity of the saturation extract is more than 4 mmhos/cm. at 25° C. and the exchangeable-sodium-percentage is less than 15. Ordinarily, the pH is less than 8.5. These soils correspond to Hilgard's (1906) "white alkali" soils and to the "Solonchaks" of the Russian soil scientists. When adequate drainage is established, the excessive soluble salts may be removed by leaching and they again become normal soils. Saline soils are often recognized by the presence of white crusts of salts on the surface. Soil salinity may occur in soils having distinctly developed profile characteristics or in undifferentiated soil material such as alluvium.

The chemical characteristics of soils classed as saline are mainly determined by the kinds and amounts of salts present. The amount of soluble salts present

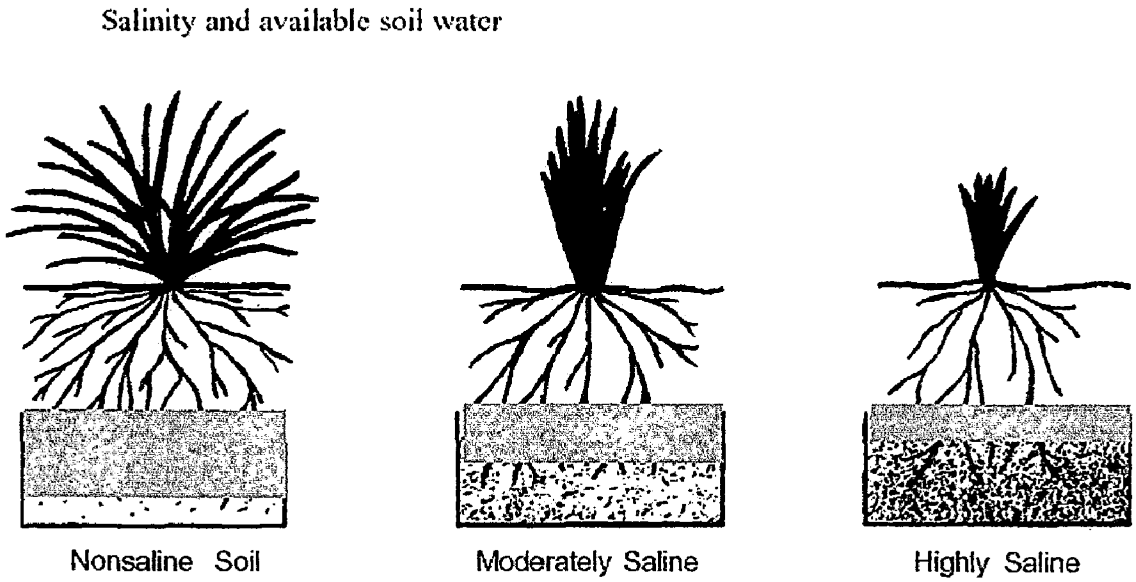


Fig. 2.2
No colour shows unavailable water. Colour shows available water

controls the osmotic pressure of the soil solution. Sodium seldom comprises more than half of the soluble cations and hence is not adsorbed to any significant extent. The relative amounts of calcium and magnesium present in the soil solution and on the exchange complex may vary considerably. Soluble and exchangeable potassium are ordinarily minor constituents, but occasionally they may he major constituents. The chief anions are chloride, sulfate, and sometimes nitrate. Small amounts of bicarbonate may occur, but soluble carbonates are almost invariably absent. In addition to the readily soluble salts, saline soils may contain salts of low solubility, such as calcium sulfate (gypsum) and calcium and magnesium carbonates (lime).

Owing to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils generally are flocculated; and, as a consequence,

the permeability is equal to or higher than that of similar nonsaline soils.

2.5.2 SODIC SOILS

a. Saline-Alkali soils

Saline-alkali is applied to soils for which the conductivity of the saturation extract is greater than 4 mmhos/cm. at 25" C. and the exchangeable-sodiumpercentage is greater than 15. These soils form as a result of the combined processes of salinization and alkalization. As long as excess salts are present, the appearance and properties of these soils are generally similar to those of saline soils. Under conditions of excess salts, the pH readings are seldom higher than 8.5 and the particles remain flocculated. If the excess soluble salts are leached downward, the properties of these soils may change markedly and become similar to those of nonsaline-alkali soils. As the concentration of the salts in the soil solution is lowered, some of the exchangeable sodium hydrolyzes and forms sodium hydroxide. This may change to sodium carbonate upon reaction with carbon dioxide absorbed from the atmosphere. In any event, upon leaching, the soil may become strongly alkaline (pH readings above 8.5), the particles disperse, and the soil becomes unfavorable for the entry and movement of water and for tillage. Although the return of the soluble salts may lower the pH reading and restore the particles to a flocculated condition, the management of saline-alkali soils continues to be a problem until the excess salts and exchangeable sodium are removed from the root zone and a favorable physical condition of the soil is reestablished.

Saline-alkali soils sometimes contain gypsum. When such soils are leached, calcium dissolves and the replacement of exchangeable sodium by calcium takes t)lace concurrently with the removal of excess salts.

b. Nonsaline-Alkali Soils

Nonsaline-alkali is applied to soils for which the exchangeable-sodium-percentage is greater than 15 and the conductivity of the saturation extract is less than 4 mmhos/cm. at 25^0 C. The pH readings usually range between 8.5 and 10. These soils correspond to Hilgard's "black alkali" soils and in some cases to "Solonetz," as the latter term is used by the Russians. They frequently occur in semiarid and arid regions in small irregular areas, which are often referred to as "slick spots." Except when gypsum is present in the soil or the irrigation water, the drainage and leaching of salinealkali soils leads to the formation of nonsaline-alkali soils. As mentioned in the discussion of saline-alkali soils, the removal of excess salts in such soils tends to increase the rate of hydrolysis of the exchangeable sodium and often causes a rise of the pH reading of the soil. Dispersed and dissolved organic matter present in the soil solution of highly alkaline soils may be deposited on the soil surface by evaporation, thus causing darkening and giving rise to the term "black alkali."

If allowed sufficient time, nonsaline-alkali soils develop characteristic morphological features. Because partially sodium-saturated clay is highly dispersed, it may be transported downward through the soil and accumulate at lower levels. As a result, a few inches of the surface soil may be relatively coarse in texture and friable; but below, where the clay accumulates, the soil may develop a dense layer of low permeability that may have a columnar or prismatic structure. Commonly, however, alkali conditions develop in such soils as a result of irrigation. In such cases, sufficient time usually has not elapsed for the development of the typical columnar structure, but the soil has low permeability and is difficult to till.

The exchangeable sodium present in nonsaline-alkali soil may have a marked influence on the physical and chemical properties. As the proportion of exchangeable sodium increases, the soil tends to become more dispersed. The pH reading may increase, sometimes becoming as high as 10. The soil solution of nonsaline-alkali soils, although relatively low in soluble salts, has a composition that differs considerably from that of normal and saline soils. While the anions present consist mostly of chloride, sulfate, and bicarbonate; small amounts of carbonate often occur. At high pH readings and in the presence of carbonate ions, calcium and magnesium are precipitated; hence, the soil solutions of nonsaline-alkali soils usually contain only small amounts of these cations, sodium being the predominant one. Large quantities of exchangeable and soluble potassium may occur in some of these soils.

The sodicity makes the bad structure of soils. This can be explained by double layer theory as given below:-

2.6 Structure of clay - An Explanation

If the soil contain appreciable amount of clay, an important feature of the soil in addition to its texture is its strucure. The strucure of the soil depends on the arrangement of clay particles. Depending on the type of ions that are adsorbed to the clay, clay particles can be dispersed as individual particles or they may be flocculated to form flocs and structural units (soil aggregates) that may be several millimeters in size. A soil with its clay in flocculated condition behaves like a coarser-textured soil than when its clay is dispersed. Whether a clay is dispersed or flocculated depends on how far the individual clay particles are separated from each other by the thickness of the layer of adsorbed cations surrounding each particle. If the clay particles can be close together, the attractive van der Waals forces are dominant and the clay particles are kept some distance apart, the repulsive electrostatic forces are dominant and the clay is dispersed.

Clay particles are negatively charged colloidal minerals, which can absorb cations (H^+, Na^+, K^+, NH^+, Ca^{2+}, Mg^{2+}, etc.) from the soil water or, rather, the soil solution. The negatively charged surface of a clay particle and the surrounding mantle of adsorbed cations are called the **double layer**. If the predominant cation in the double layer is Na^+, the individual clay particles cannot come close together because the Na^+ ions are surrounded by water molecules or are hydrated, producing a thick double layer (Fig. 2.3). Also, the monovalent Na^+ ions do not effectively mask the negative charges of the clay particles themselves. For Na^+ clays, therefore, the repulsive electrostatic forces between the negatively charged particles exceed the attractive van der Waals forces, causing the clay particles to exist as separate particles in a dispersed or deflocculated condition. This dispersion occurs already if 10 to 20 percent of the adsorbed cations consists of Na^+. Soils with Na clay have a poor "structure". They have a tendency to seal. They are low in permeability, are sticky and amorphous, and become hard upon drying.

If the catons in the double layer around the clay particles are mainly Ca^{2+} and Mg^{2+}, the clay particles can come much closer together (Fig. 2.4) This is because Ca^{2+} and Mg^{2+} are not hydrated and are thus of smaller size. Also, these cations are divalent, producing better masking of the negative charges of the clay particles. Since the van der Waals forces increase very rapidly with decreasing distance between the clay particles, the attractive forces are dominant and the clay particles cling together to form flocs and aggregates. A soil with predominantly Ca or Mg clay behaves like a coarser-textured soil and has a "good" structure. Such soils are more permeable and friable than soils with dispersed clay.

Clay can be converted from a dispersed state to a flocculated condition by changing the adsorbed ions from Na^+ to Ca^{2+} or Mg^{2+}. This can be done through the process of cation exchange, adding a soluble Ca salt to the soil.

A flocculated clay and associated "good" structure of the soil are preferred for agriculture. Thus, irrigation water should not contain too much Na^+ because this could cause the clay to become dispersed and the soil structure to deteriorate. An example of what can happen to a soil when the predominant ion in the double layer changes from Ca^{2+} to Na^+ is "the destruction of acres of prime farm land" caused by the wrong neutralizer to correct the effects of an accidenal acid spill from a derailed train in Canada (Ground Water Newsletter, 1974). Instead of using a lime or other calcium salt, sodium carbonate and sodium hydrochloride were applied to the land to raise the pH of the soil. This cause dispersion of the clay and associated deterioration of the soil structure. Conversely, Ca clays have been deliberately dispersed and sealed by applying soda ash to reduce seepage losses from ponds (Reginanto et el., 1973)

Whether a clay is dispersed or flocculated also depends on the salt concentration of the soil solution. A high concentration of NaCl in the soil water, for example, could still cause a Na clay to be flocculated. The high ionic strength of the solution in that case compresses the double layer, allowing the clay particles to be sufficiently close to each other for the van der Waals forces to be dominant. For this reason, clay in a soil flooded with seawater will remain flocculated. Deflocculation will start only when seawater is leached out by rain, which causes the NaCl concentration in the soil solution to decrease. When this happens, lime or calcium should be added to the soil to minimize deterioration of its structure.

2.6.1 Adsorption Reactions

Adsorption is arguably the most important of physical-chemical process responsible for the retention of inorganic and organic substances in the soil environment. The soil solution composition of inorganic and organic substances is controlled by surface or near-surface process. With respect to trace elements, the activities of aqueous metal ions in equilibrium with an adsorbed phase are controlled to levels that that can be orders of magnitude lower than levels controlled by even the most stable mineral phase. Strictly defined, adsorption is a surface process that results in the accumulation of a dissolved substance (an adsorbate) at the interface of a solid (the adsorbent) and the solution phase. This interfacial region incorporates the volume of the soil solution that is commonly referred to as the solid-solution interface. The process of adsortion can be controlled with that of precipitation, in which the crystal structure of a minaral increases in volume as a result of the three-dimensional growth of the structure. Inorganic and organic substances can also be retained through the process of adsorption. In this process, a substance diffuses into the three-dimensional framework of a solid- structure. Partitioning (adsorption) is a mechanism that is frequently responsible for the retention of organic compounds by soil organic matter.

DOUBLE LAYER THEORY

Sodium as Cat ions:-

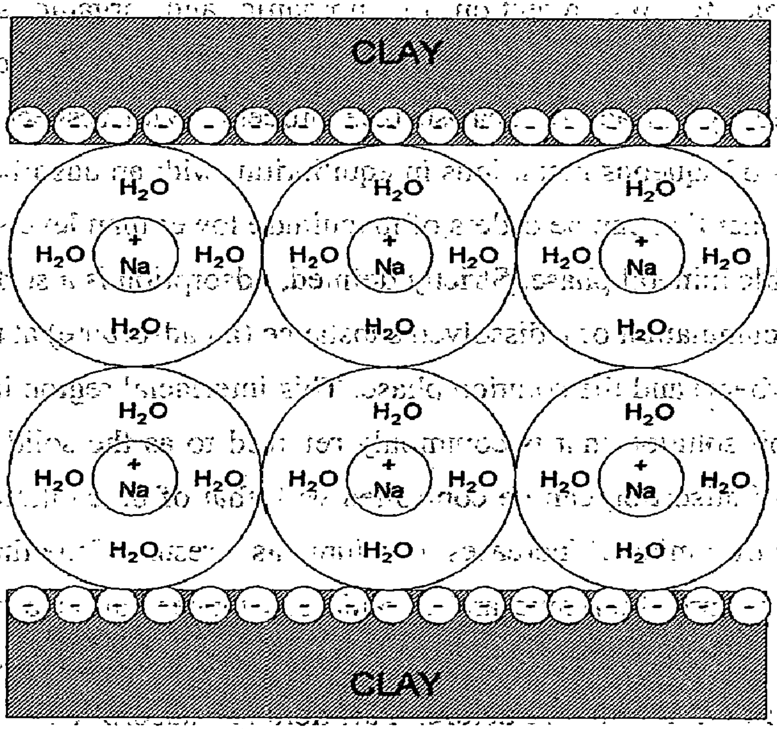


Fig. 2.3

Calcium as Cat ions:-

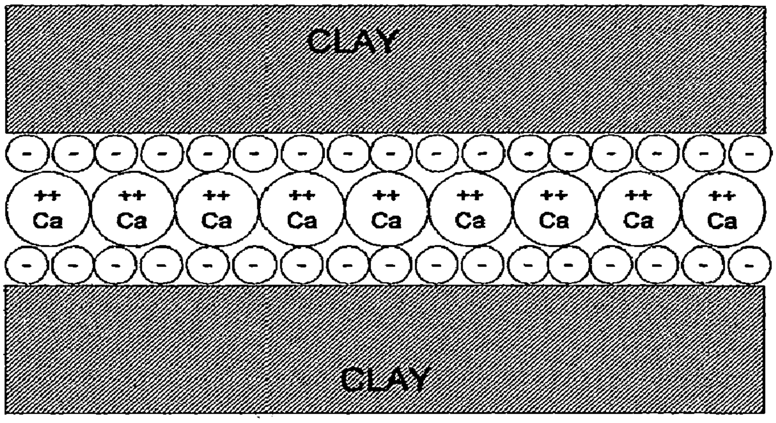


Fig. 2.4

2.7 GENESIS AND MANAGEMENT OF SODIC SOILS

Sodic soils most commonly occur as a result of natural processes (primary sodification). The nature of the parent material and the subsequent pedogenic process dictate sodic soil development. Cnditions that promote the formation of sodic soils include the presene of shallow saline groundwater or a perched water table (within 1.5 m of the surface), soil water rich in bicarbonate, impede drainage, low slope, and textural discontinuities. Sodic, or black alkal, soils are associated with the presence of Na_2CO_3, high ESP values, and pH values greater than 9.0 (a consequence of the high Na_2CO_3 content). Secondary sodification is a process that occures as a result of anthropogenic activities, where the development of a soil with sodic properties results from poor irrigation water management and poor drainage (water logging).

The natural formation of a sodic soil is closely tied to sulfate reduction in water-saturated systems. The neccessary ingredients for primary sodic soil formation are impeded drainage, a shallow groundwater that is high in sulfate, high soil organic matter, and a reducing environment at the groundwater interface. The reduction of sulfate produces alkalinity (consumes protons):

$$SO_4^{2-}(aq) + 2H(aq) \rightarrow H_2S(gas) + 2O_2(gas) \qquad 2.1$$

The decomposition of organic matter produces CO_2, which is adsorbed by the alkaline water to form HCO_3. The displacement of Ca^{2+} and Mg^{2+} from the exchange complex by Na^+ is favored as a result of calcite precipitation:

$$(Ca^{2+} + Mg^{2+})X_2(ex) + 2Na^+(aq) \rightarrow 2NaX(ex) + (Ca^{2+} + Mg^{2+})(aq) \qquad 2.2$$

$$(Ca^{2+} + Mg^{2+})(aq) + HCO_3^-(aq) \rightarrow (Ca, Mg)CO_3(s) + H^+(aq) \qquad 2.3$$

The high sulfate levels in the shallow groundwater can also provide favourable conditions for gypsum [$CaSo_4.2H_2O$] precipitation, again favouring the retantion of Na^+ on the exchange complex by removing dissolved Ca^{2+} from the soil solution:

$$Ca^{2+}(aq) + SO_4^{2-}(aq) + 2H_2O(l) \rightarrow CaSO_4.2H_2O \qquad 2.4$$

Excess bicarbonate coupled with elevated Na^+ levels result in the production of $NaHCO_3$. Finally, dehydration favours Na_2HCO_3 formation:

$$2NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O \qquad 2.5$$

As a result, a high ESP characterizes the exchange complex, high SAR and high pH characterizes the soil solution (controlled by $Na_2 Co_3$), and calcite is present in the soid phase.

The impact of excessive sodicity on the permeability of the soils is intimately associated with the salinity of the soil solution. The degrative effects of sodium on soil structural properties can be overcome by two principle mechanisms, acting alone or in concert: (1) displacement of Na^+ from the soils exchange complex by divalent cations (the reason is explained previously by the double layer theory), or (2) increasing the salinity of the soil solution. These two mechanisms are complementary with regard to their beneficial effects on sodic soils. Irrigation with saline irrigation water may be initially employed to stabilize soil structure and increase soil stability. However, increasing soil salinity is less effective in clayey, smectitic soils (which tend to remain relatively impermeable irrespective of EC). Increasing the salinity of a soil solution also increases the threshold ESP, the ESP bellow which flocculation occurs. Increased permeability allows for the removal of soluble components that might interfere with reclamation (such as soluble sulfate when gypsum is the amendment) and the effective infusion of divalent cations necessary for sodic soil reclamation.

The reclamation of a sodic soil requires adequate drainage, leaching, and a source of Ca^{2+}, calcium, which is required to displace Na^+ from the exchange complex, can be derived from a number of sources. Chemical amendments that supply Ca^{2+} include gypsum and $CaCl_2$. If calcite is present in the soil, H_2SO_4 can be used to dissolve calcite. Highly saline water may also be employed to hasten Na^+ displacement by relying on the valence dilution effect. In this procedure, a sodic soil is initially leached with highly saline, low SAR water, which also increases permeability. With each successive treatment, the irrigation water is diluted with high-quality (less saline) water. The dilution favours the displacement of Na^+ by divalent cations, and leaching removes the soluble Na^+. Irrespective of the mechanism used to reduce SAR and ESP, leaching to remove Na^+ from the soil profile is a necessary.

2.8 CATION EXCHANGE:

Before the year 1850, the belief that soil was an inert material was prevalent among agricultural scientists. Even Justus von Liebig, a revered agricultural chemist of the period, the first to demonstrate that plants obtain mineral nutrients from soil and the first to recognize that the addition of a single essential nutrient would increase crop yield only if all other nutrients were present in sufficient levels (Liebig's "Law of the Minimum"), espoused the belief that soil was merely a nonreactive filter and support media for plants. However, all this changed in 1845 when an agriculturist and Yorkshire farmer named Harris Stephan Thompson performed a small series of experiments (Thompson, 1850). To glass columns containing a "*light sandy loam of good quality*", a "*black soil (from the bottom of the old stick heap)*", and a "*strong clay soil*", Thompson added a $(NH_4)_2SO_4$ solution. Upon leaching each column with a volume of water that exceeded "*in amount the heaviest continuous fall of rain which is ordinarily experienced in this country*", a leachate was obtained which, when dried, yielded a precipitate that was found to be principally gypsum ($CaSO_4.2H_2O$), as "*the whole of the ammonia was retained by the soil*".

In 1848, H.S. Thompson related to John Thompson Way, a consulting chemist to the Royal Agricultural Society, the results described above. In addition, a Dorset farmer named Huxtable related to Way that, "*he made an experiment in the filtration of the liquid manure in his tanks through a bed of an ordinary loamy soil; and that after its passage through the filter-bed, the urine was found to be deprived of colour and smell - in fact, that it went in manure and came out water*", (Way, 1850). The findings of Huxtable, and particularly the quantitative findings of Thompson, lead J.T. Way (Way, 1850) to perform the first comprehensive studies of the process later termed base exchange. Way's studies were principally confined to two soils, a "red" soil from Berkshire and a loam from Dorestshire Downs, although white pottery clay, washed sand, red brick dust, powdered tobacco pipe (composed of clay), and aluminosilicate precipitates wre also used. In general, Way's experiments consisted of passing solutions of common salts (including NH_4, K, Na, Mg, and Ca salts of OH, SO_4, Cl, NO_3, and CO_3) through columns or filter beds of the various materials. In addition, experiments were conducted using soil particle size separates, dried soil (50 to 60^0C), combusted soil, and HNO_3- and HCl- digested materials. Soil leachates of sodium phosphate solution, gunao extract, human urine, flax water, sewer water, and Thames River water were also examined. The results and conclusions of J.T. Way were revolutionary (from Way, 1852; the salient statements are in bold):

> it was found that ordinary soils possessed the power of separating from solution in water the different earthy and alkaline substances presented to them in manure; **thus, when solutions of salts of ammonia, of potash, magnesia, &c., were made to filter slowly through a bed of dry soil, 5 or 6 inches deep, arranged in a flower-pot or other suitable vessel, it was observed that the liquid was first ran through no longer containing any of the ammonia or other salt employed.**
>
> But further, this power of the soil was found not to the whole salt of ammonia or potash, but only to the alkaly itself. **If, for instance, sulphate of ammonia were the compound used in the experiments, the ammonia would be removed from solution, but the filtered liquid would contain sulfuric acid in abundance - not in the free or uncombined form, but united with lime; ... and this result was obtained whatever the acid of the salt experienced on might be.**
>
> It may be mentioned, also, in this place, that, at a later period of the investigation, it was satisfactorily proven that **the quantity of lime acquired by the solution correspondsd exactly to that of the ammonia removed from it.- the action was therefore a true chemical decomposition.**
>
> Again, it was found that **the combination between the soil and the alkaline substances was rapid, if not instantaneous,** partaking therefore of the nature of the ordinary union between an acid and alkali. In the course of these experiments several different soils were operated upon, and it was found that all soils capable of profitable cultivation possessed the property in question in a greater or lesser degree. **It was shown that the power to absorb alkaline substances did not exist in sand; that the organic matters of the soil had nothing ti do with it;** that the addition of carbonate of lime to a soil did not increase its absorptive power for these salts; and indeed that a soil in which carbonate of lime did not occur, might still possess in a high degree the power of removing ammonia or potash from solution, and **it was evident that the active ingredient in all thase cases was clay.**

In addition to the above findings, Way also observed the complete soil removal of phosphorus from guano extract and sodium phosphate leachates (a result that Way attributed to the formayion of calcium phosphate precipitates, rather than "absorption"), that the acid digestion of soil did not destroy the absorptive power, and that the combustion of soil or clay diminished the ability of the material to absorb. An initial conclusion of J.T. Way - that organic matter is unimportant in cation retention - was later refited through the work of Samuel W. Johnson (1859), who noted that swamp-muck was "capable of absorbing 1.3 per cent of ammonia, while ordinary soil absorbs but 0.5 to 1 per cent." The experiments of Way were limited to exchange reactions involving the displacement of native Ca^{2+} by the common cations, Na^+, K^+, NH^+_4, and Mg^{2+}. Indeed, until the work of J.M. van Bemmelen in the 1880s, it was generaly thought that only Ca^{2+} was displaced from soils by exchange reactions, although Way himself noted the appearance of more Na^+ in white clay, which we find from the analysis contains this alkali in considerable quantity. It would seem, therefore, that in the present instance soda, and not lime, had acted the part of the substituting base" (Way, 1852).

2.8.1 QUALITATIVE ASPECTS OF CATION EXCHANGE

With the exception of a small number of misinterpretations, the conclusions of J.T. Way have stood as the defining characteristics of cation exchange reactions. Ion exchange reactions are reversible, rapid (rate is cotrolled by site accessibility and is said to be diffusion controlled), and stoichiometric with respect to charge. The following exchange reactions illustrate the stoichiometric and equivalent replacement of an ion on the exchange complex by an ion from the aqueous phase:

$$0.5CaCl_2\,(aq) + Mg_{0.5}X(eq) \rightarrow Ca_{0.5}X(eq) + 0.5MgCl_2\,(eq) \qquad 2.6$$

$$NH^+_4(aq) + Ca_{0.5}X(ex) \rightarrow NH_4X(ex) + 0.5Ca^{2+}(aq) \qquad 2.7$$

$$K^+(aq) + Al_{0.33}X(ex) \rightarrow KX(ex) + 0.33\,Al^{3+}(aq) \qquad 2.8$$

where X⁻ represents an equivalent of exchange phase charge. In the cotext of exchange reactions, the equivalent quantity of a cation may be described as the moles of cation that replace a mole of hydrogen ions. Since a mole of proton is identical to a mole of charge (mol_c), an equivalent quantity of a cation may also be described as the moles of cation that are equivalent to a mole charge. For example, ⅓ mole of Al^{3+} is equivalent to 1 mol charge (a mole of Al^{3+} is equivalent to 3 mol of charge), a mole of

Ca^{2+} or Mg^{2+} is equivalent to 2 mol of charge, and a mole of NH^+_4 or K^+ is equivalent to 1 mol of charge. In equations a to c, one equivalent of exchange phase charge (the same as one mole of exchange phase charge) is satisfied by one equivalent of exchangeable cations. Thus, one mole of NH^+_4 or K^+, $^1/_2$ mol of Ca^{2+} or Mg^{2+}, or $^1/_3$ mol of Al^{3+} satisfies a mole of exchange charge. The cation exchange reactions also illustrate the exchange stoichiometry. For example, displacement of one equivalent of Al^{3+} from the exchange phase requires one equivalent of K^+, or 3 mol of K^+ are required to displace 1 mol of Al^{3+}.

Equations a to c correctly display cation exchange equilibria for Mg^{2+}-Ca^{2+}, Ca^{2+}-NH^+_4, and Al^{3+}-K^+ exchange, as the requirements of charge and mass are satisfied. Ion exchange reactions may also be expressed, for example, as indicated for Ca^{2+}-NH^+_4 exchange:

$$2NH^+_4\,(aq) + CaX_2\,(ex) \rightarrow 2NH_4X\,(ex) + Ca^{2+}\,(aq) \qquad 2.9$$

$$2NH^+_4\,(aq) + CaX\,(ex) \rightarrow (NH_4)_2X\,(ex) + Ca^{2+}\,(aq) \qquad 2.10$$

where X^- represents a mole of exchange phase in Equation 2a (as in Equation b), and X^{2-} represents two moles of exchange phase charge in Equation 2b. Both reactions in Equation 2 satisfy mass and charge balance requirements, and are equally valid machanisms for describing the Ca^{2+}-NH^+_4 exchange process (alongwith Equation b). Finally, exchange reactions are also qualified with respect to the nature of the ions involved in the process. Equation a is an example of a symmetrical (homovalent) cation exchange reactions, as the ions involved have the same charge. Equations b and c and 2a and 2b are examples of nonsymmetrical (heterovalent) cation exchange reactions, as the ions involved have unequal charge. Equations b and 2a and 2b are uni-bivalent exchange reactions; Equation c is a uni-trivalent exchange reaction.

The use of equivalents to describe chemical behavior (as in ion exchange) or ion concentrations is no longer an acceptable practice. Prior to the favoured use of SI units in the soil science, it was common to express the concentrations of ions in soil solutions in terms of normality (N), eq L^{-1} or meq L^{-1}, and the cation exchange capacity of a soil in meq 100 g^{-1} (milliequivalent per 100 grams). The composition of a soil solution that contains 10 meq L^{-1} Na as Na^+ and 10 meq L^{-1} Ca as Ca^{2+} contains

10 mmol L^{-1} Na and 5 mmol L^{-1} Ca; assuming that an equivalent is defined as the moles of a substance that are identical to a mole of charge. One of the ambiguities associated with the use of equivalent units demonstrated in the above example. Expressing the total concentration of a dissolved substance in equivalent units requires an assumption relative to ion speciation. Implicit in the 10 meq L^{-1} Ca concentration is the assumption that Ca exists and reacts as the divalent ion, even though a significant proportion of the total soluble Ca may exist in ion pairs (e.g. $CaCl^+$ and $CaSO^0_4$) or organic complexes (which are species that will not replace two equivalents of proton charge).

An additional ambiguity in the use of equivalents is that the units is specific to the type of chemical reaction that occurs. For example, in the exchange reactions:

$$FeCl_2(aq) + 2KX\ (ex) \rightarrow FeX_2\ (ex) + 2KCl\ (aq) \qquad 2.11$$

$$FeCl_3\ (aq) + 3KX\ (ex) \rightarrow FeX_3\ (ex) + 3KCl\ (aq) \qquad 2.12$$

1 mol of Fe^{2+} in Equation 3a will replace 2 mol of K^+. Similarly, 1 mol of Fe^{3+} in Equation 3b will replace 3 mol of K^+. Thus, the equivalent mass of Fe^{2+} (g eq^{-1}) is one half the molar mass (g mol^{-1}) of Fe, and the equivalent mass of Fe^{3+} is one third the malar mass of Fe (there are 2 eq mol^{-1} of Fe^{2+}). However, in redox reactions, the equivalent quantity of a cation may be described as the moles of cation that are equivalent to a mole of electrons transferred. For example, in the reaction:

$$FeCl_2(aq) + 0.25\ O_2(g) + HCl(aq) \rightarrow FeCl_3(aq) + 0.5\ H_2O(l) \qquad 2.13$$

both Fe^{2+} and $Fe^{3+}$are capable of donating and accepting only one electron; thus, the equivalent masses of Fe^{2+} and Fe^{3+} are identical to the molar mass of Fe (1 eq mol^{-1} of Fe^{2+} and 1 eq mol^{-1} of Fe^{3+}). Therefore, a solution that contains 10 meq L^{-1} $FeCl_3$ may contain 3.3 mmol L^{-1} $FeCl_3$ if Equation 3b is the reaction of interest, or 10 mmol L^{-1} if Equation 4 is the reaction of interest. Because there is no ambiguity in the use of molar concentration units, their use is favored.

Ion exchange reactions abide by the Law of Mass Action and respond to perturbayions of the soil chemical environment as described by Le Chatelier's principle. For the reaction,

$$2Na^{+}(aq) + CaX_2(ex) \rightarrow 2NaX(ex) + Ca^{2+}(aq) \qquad 2.14$$

the retention of Ca^{2+} is favored if the system initially contains equal concentrations of soluble Ca^{2+} and Na^{+} (retention of higher valence species is favored). Le Chatelier's principle states that when a stress is brought upon a system at equilibrium, a change will occur such that the equilibrium is displaced in a direction that tends to undo the effect of the stress. Although the retention of the Na^{+}ion is not favored over Ca^{2+}, it can be forced onto the exchange complex by any stress that disturbs the equilibrium in favor of the formation of NaX. Thus, any process that increases Na^{+} in the solution or removes soluble Ca^{2+} will increase NaX and decrease CaX_2 concentrations. For example, loading the system with Na^{+}, forming a Ca precipitate, or forming Ca^{2+}ion pairs (e.g., $CaSO^{0}_{4}$) will favor the formation of NaX by forcing Equation 5 to proceed further to the right in response to the stress placed on the equilibrium of the system. A soil can be Na^{+} saturated, irrespective of the native exchange phase composition, by a sequential centrifuge washing technique. In this technique, the soil is reacted with a concentrated (1 M) NaCl solution in a centrifuge tube. The suspension is centrifuged, the supernatant liquid is removed and replaced by another aliquot of NaCl solution, and then the process is repeated (a minimum of three times). The high concentration of NaCl in the equilibrium solution stresses the system and favors the displacement of Ca^{2+} and other native cations, which are removed in the suenatant after centrifugation, leaving the soil exchange complex Na^{+} saturated.

A characteristic of nonsymmetric ion exchange reactions is that the dilution of a solution in equilibrium with the exchanger phase favors the retention of more highly charged exchangeable ion. This characteristic is known as the valence dilution effect, and has been useful in the reclamation of sodic environments. Correspondingly, increasing the salt content of the equilibrating solution (e.g., through evaporation) will result in the preferential retention of the lower valence ion. For the reaction:

$$2Na^{+}(aq) + CaX(ex) \rightarrow Na_2X(ex) + Ca^{2+}(aq) \qquad 2.15$$

where X^{2-} represents 2 mol of surface charge, the Law of mass Action states that an exchange selectivity coefficient (reaction quotient), K_s, may be written:

$$K_s = \{Na_2X\}[Ca^{2+}] / \{CaX\}[Na^+]^2 \qquad 2.16$$

where {} and [] denote effective concentration variables of the exchange and aqueous phase species. Rearranging Equation 6b yields:

$$K_s.[Na^+]^2 / [Ca^{2+}] = \{Na_2X\}/\{CaX\} \qquad 2.17$$

If $[Na^+] = [Ca^{2+}] = 1.0$ in the equilibrating solution, Equation 2.17 reduces to:

$$K_s = \{Na_2X\}/\{CaX\} \qquad 2.18$$

If this solution is subjected to a tenfold dilution, as might occur during a rainfall event, then $[Na^+] = [Ca^{2+}] = 0.1$. When the exchange and solution phases have reequilibrated, the new equilibrium condition, according to Equation 6c is:

$$K_s.[0.1]^2 / [0.1] = 0.1K_s = \{Na_2X\}/\{CaX\} \qquad 2.19$$

In this example, a tenfold decrease in concentration in the equilibrating solution will result in a tenfold decrease in the ratio of Na to Ca on the exchange complex, if K_s is assumed to remain constant; or a tenfold increase in the ratio of Ca to Na on the exchange complex (ten times as much Ca^{2+} as Na^+ on the exchange phase relative to the original system). Thus, dilution of a solution in equilibrium with an exchange phase will favor the retention of the more highly charged exchangeable ion.

Exchangeable cations are highly hydrated and do not actually form chemical bonds with the absorbing surface. Instead, exchangeable cations are held at the surface through an electrostatic interaction and their retention is influenced by the variables described in Coulmb's law:

$$F = q_+ . q_- / \varepsilon r^2 \qquad 2.20$$

As this equation states, the force of attraction (F) between opposing charges is directly related to the magnitude of the charges q_+ and q_- and inversely related to the square of the separation distance r in a uniform medium having a dielectric constant ε. Therefore, the effective size and valence of an exchangeable ion determine its exchangeability. The ease with which adsorbed ions can be displaced from the surface by completing ions can be predicted from siz and valance parameters. As the valence of an exchangeable cations increases, so does the force of attraction to a charged surface. The greater the valence, the greater is the selectivity of the surface for the cation. Further, for a given valence, the hydrate radius of an ion determines exchangeability. As the hydrated radius of an exchangeable cation decreases (r decreases), the force of cation attraction to a charged surface increases.

The relative replaceability of exchangeable cations (ease of removal) is described by a lyotropic series. Beginning with the most easily removed cation, the lyotropic series for the monovalent and divalent exchangeable cations are (hydrated radii in nanometers are displayed n parentheses):

$$Li^+ (0.382) \approx Na^+ (0.358) > K^+ (0.331) \approx NH^+_4 (0.331) > Rb^+ (0.329) > Cs^+ (0.329)$$

and

$$Mg^{2+} (0.428) > Ca^{2+} (0.412) > Sr^{2+} (0.412) \approx Ba^{2+} (0.404)$$

All cations may participate in cation exchange reactions, even though some may also participate in specific retention processes with surface functional groups. Thus, the lyotropic series can be expanded to include trace metal cations:

$$Li^+ (0.382) > Na^+ (0.358) > NH^+_4 (0.331) > K^+ (0.331) > Rb^+ (0.329) > Cs^+(0.329) > Ag^+(0.341)$$

and

$Mg^{2+}(0.412) > Zn^{2+}(0.430) > Co^{2+}(0.423) > Cu^{2+}(0.419) > Cd^{2+}(0.426) > Ni^{2+}(0.404) > Ca^{2+}(0.412) > Sr^{2+}(0.412) > Pb^{2+}(0.412) > Ba^{2+}(0.404)$

2.8.2 CATION EXCHANGE CAPACITY

The cation exchange capacity (CEC) of a soil can be defined as the moles of adsorbed cation charge that can be displaced by an index ion per unit mass of soil. More critically, CEC is defined as the total charge excess of cations over anions in the os- and d-planes, under stated (controlled) conditions of temperature, pressure, soil solution compositio, soil-to-solution mass ratio, and other method dependable variables. The CEC is expressed in units of $\text{cmol}_c\ \text{kg}^{-1}$, which are equivalent to the units of $\text{meq}\ 100\ \text{g}^{-1}$ common in the early literature (i.e., $1\ \text{cmol}_c\,\text{kg}^{-1} = 1\ \text{meq}\ 100\ \text{g}^{-1}$). In general, the reported CEC of a soil often refers to the maximum negative surface charge and indicates the potential CEC of the soil. The potential CEC of a soil indicates surface charge arising from constant charge surfaces (from isomorphic substitutio) and deprotonated inorganic surface functional groups and organic functional groups.

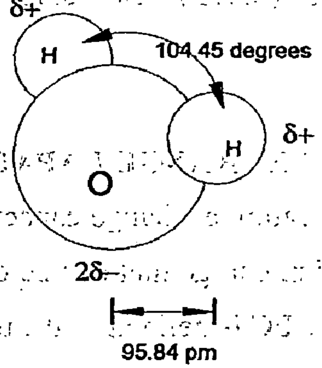
2.9 NATURE OF WATER

Water is highly reactive substance and an exceedinglty effective solvent. It is a compound that has a high dielectric constant, which is a measure of a solvent's ability to overcome the attraction between a dissolved cation and an anion. The dielectric constant may be defined as the ability to oppose the electrical attraction between ions of opposite charge. This definition is illustratated mathematically in the expression:

$$F = \left(\frac{Z_- Z_+}{r^2}\right)\left(\frac{1}{\varepsilon}\right) \qquad 2.21$$

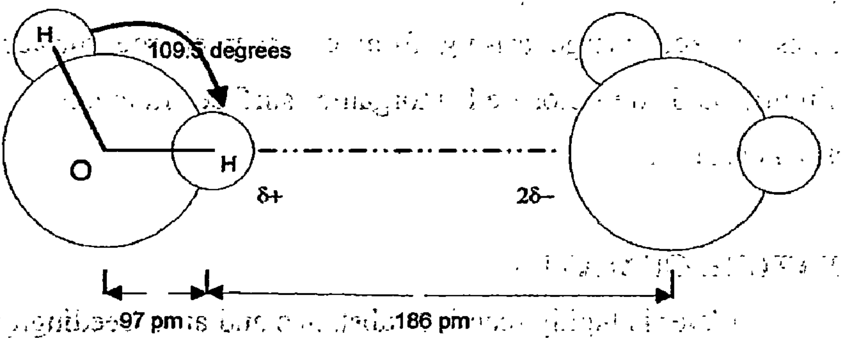
where F is the force of attraction between ions of opposite charge of magnitude Z_- and Z_+ that are separated by a radius of r in a solution having a dielectric constant ε. The force of attraction between two oppositely charged ions will be less in solvents that have high dielectric constants, relative to solvents that have low dielectric constants.

A relatively high dielectric constant is a rather unique property of water that is a result of a nonlinear molecular configuration as shown below:-



Isolated Water Molecule

Fig. 2.5



Water Molecules in Liquid

Fig. 2.6

Note : – The figure shows the Physical Characteristics of an isolated water molecule and two water molecules assotiated through a hydrogen bond. δ^+ and $2\delta^-$ represent the partial positive and negative charges on the proton and oxygen, $\delta = 0.42$ (Reference : Mahoney and Jorgenser, 2000). The bond energy of the covalent O – H bond in the water molecule is 470 kJ mol^{-1}, while the bond energy of the hydrogen bond between water molecules is approximately 23.3 kJ mol^{-1} (Suresh and Naik 2000).

2.10 NATURE OF SURFACES OF CLAY MINERALS

Because of the complex character of water many aspects of the structure of minerals can be of influence, but those associated with the surface, both externally and internally, are the most important.

Basically, three features of crystal surfaces may influence water molecules which come into contact with them:

1. Distorted ionic groupings in surface layers.
2. Broken bonds at fracture or cleavage planes.
3. Unscreened ions (usually cations) associated with the lattice.

Surfaces can atract water molecules to themselves to form layers where a type of structure exists very different from the condition in liquid water.

Over and above adsorption phenomenon due to surfaces are effects attributed to ionic inclusions within the crystel lattice itself. The presence of weakly-held cations, as counter-balancing charges in a loosely packed structure, invariably leads to hydration effects. In an aqueous medium, cation which are not fully electrically bonded will adsorb water molecules to complete their screening within the lattice. Some lattice in which ions are not correctly or adequately co-ordinated possess this same property and the cations adsorb water molecules to become hydraes. Similar effects are observed in clay minerals such as montmorillonites with loosely-held counter-balancing cations. Where the are contained in a specific layer, the adsorption of such water can cause major swelling of the lattice itself. The amount of ionic adsorption depends on the nature of the cation and on the relative humidity of the system (Mering, J., Trans. Farad. Soc. 42B, 205, 1946).

2.11 The SOLID-SOLUTION Interface: *A microscopic View*

The solid-solution interface is a transitional zone that is neither mineral nor bulk solution. The interfacial region exists because soil moisture bear electronic charge and metal and ligand complexation capabilities. The interfacial region of the soil consists of adsorbed protons, metals, and ligands, and an interfacial solution phase. The composition of the interfacial phase is directly influenced by the structural, chemical, and electrochemical aharacteristics of the soil minerals and the chemical acracteristics of the bulk soil solution. Actually, two types of surface charge exists on soil minerals: structural charge and pH-dependent charge. While these two categories of charge may account for the preponderance of surface charge, they are by no means the only sources of charge on mineral surfaces.

The interfacial region between the solid and solution phases, the region that exists between structural solid and bulk solution, conceptually consists of laminated layers that differ in chemical and electrochemical characteristics. Charge development on a mineral surface and the neutralization of the charge by dissolved ions and molecules under the influence of the surface occur in the interfacial layers.

2.12 THEORY OF LEACHING

Water is the chief mode of transport of salt in the soil. There is a dynamic equilibrium between the ions in the solution phase and those which are associated with soil complex, the soluble salts and the soil minerals. The exchangeable ions mostly resides in the stern layer and are immobile with respect to moving water. The ions outside this layer are more mobile and bulk of them move out in response to the concentration gradients or as the soil solution is displaced by applied water.

There are two main processes involved in salt movement in soils:

1. Convection of dissolved salts due to mass flow of water.
2. Diffusion of salt in response to the concentration gradient. The extent and direction of salt movement is determined by concentration of salt in soil solution, the amount of solution that moves and the direction in which movement occurs.

Hence pattern of water movement has bearing with salt accumulation in soil. Diffusion depends upon concentration gradient and may add or diminish the concentration of convective flux depending upon the direction in which the concentration gradient occurs. A common problem coupled with high evaporative conditions in regions with arid and semi-arid climates is the presence of excess soluble salts in root zone. This results in larger amount of mass flow-mediated flux of solute towards roots of plants. Consequently salt concentration in the root-soil intrface region increases and the magnitude of increase depends upon evaporative demand and salt concentration of soil solution (Sinha and Singh, 1974, 1976 a, 1976 b). As a result the plant roots are exposed to a salt concentration which may be several fold of that in soil few cm away from the roots.

2.12.1 Process of Leaching

Leaching of saline soil is commonly effected by ponding of water on soil surface. If the salt removal from the soil is assumed to be a piston-flow process then the maximum quantity of water required to leach down the initial salt solution from the given soil depth would have been equal to its saturation capacity. In practice it is found that amount of water needed to accopmlish salt removal is always more than this capacity.

This is because of the charecteristic way in which the salts are displaced from soils. Salts when present at a point in a fluid flowing through porous medium spread out in a cone shaped path. Scheidegger (1954) describes this process as dispersion. Day (1956), Rifai at el. (1956) and Van der Molen (1956) reported that salt displacement in soila mainly occurs due to dispersion which is the result of variation in flow velocity of water while it moves through complex system of soil pores. The resultant mixing of flow elements causes so called miscible displacement of solutes from the soil. Bigger and Nielsen (1967) have studied the miscible displacement with regard to leaching phenomenon in soils.

Gardener and Brooks (1957) described the leaching process mathematically and worked out leaching requirements from a simple model. The model consisted of a network of uniform soil pores in which the centre of pore was assumed to move with the same velocity as that of leaching water. This fraction of salt was named mobile salt (c). The part of salt close to pore walls moved slowly and was named immobile salt (q). The ratio $\frac{c}{q} = B$, was considered a measure of quantity of water in excess of one pore volume which was required to leach down a certain percentage of original salt present in the soil. They reported that (1 + B) pore volumes of leaching water reduced the salt concentration of soil to 50 percent while (1 + 2B) pore volume reduced to 20 percent. The value of B varies with soil properties but usually ranges between o.1 to 0.4, which means that 1.2 to 1.8 pore volume of water should be passed through soils to reduce the salinity to 80 percent of the original value.

Reev at el. (1955) conducted leaching studies on a saline silty clay loam soil. Their experimental findings were approximated by the following equation:

$$\frac{D_{1w}}{D_S} = \frac{1}{5\left(\frac{C}{C_0}\right)} + 0.15 \qquad 2.22$$

Where D_{1w} is the depth of water leached through a depth of soil D_S, and C_0 and C represent the average salt concentration in the same soil depth before and after leaching. They brought out a thumb rule from the above equation. The rule is "One foot water per foot of soil depth" leaches out 80 percent of salt from the soil.

Equation ( ) can be rewritten in terms of electrical conductivity as:

$$\frac{D_{1w}}{D_S} = \frac{(EC_e)_i}{5(EC_e)_f} + 0.15 \qquad 2.23$$

Where $(EC_e)_i$ and $(EC_e)_f$ are electrical conductivities of saturation extract of soil before and after leaching respectively.

2.12.2 Water and Salt Balance of The Root Zone

W.H. Van der Molen (1972) reports the following water balance equetion of an irrigated soil:

$$I + P + G = E + R + \Delta W \qquad 2.24$$

where,

I = Effective amount of irrigated water;

P = Effective amount of precipitation;

G = Amount of Capillary rise of ground water;

E = Amount of evaporation;

R = Amount of deep percolation, and

ΔW=Change in amount of moisture stored.

I & P are defined here as effective quantities as they relate to quantities that actually infiltrates into the soil.

The salt balance equation for the root zone reads as:

$$IC_i + PC_p + GC_g = RC_r + \Delta Z' \qquad 2.25$$

where,

C = Salt concentration in meq/l;

i = Suffix denoting irrigation water;

p = Suffix denoting precipitation;

g = Suffix denoting groundwater;

r = Suffix denoting deep percolation water and

ΔZ=Change in salt content of the root zone in meq/m^2.

Since the amount of salt supplied to irrigated soils by rainfall is negligible compared with amount supplied by irrigated water, PC_p may be taken as zero. Further it is assumed that under equilibrium conditions $C_g = C_r$. Hence, Equation ( ) reduces to

$$IC_i = R^*C_r + \Delta Z' \qquad 2.26$$

where R* is the net deep percolation, equal to (R - G). In terms of gains and losses of salts the net deep percolation R* may be equal to leaching requirement.

If tha salt balance of the soil is in equilibrium $\Delta Z'$ will be zero. If it is not in equilibrium, the quantity of salts in the root zone at the bedinning of the period under consideration (Z_1') will differ from that at end (Z_2').

$$\Delta Z' = Z_2' - Z_1' \text{ (meq/m}^2\text{)} \qquad 2.27$$

2.12.3 The Leaching Efficiency

It is assumed that the amount of salt in the root zone (Z') is dissolved in the soil moisture. As downward water and salt movement in the root zone generally take place at moisture content near field capacity, logically it may be considered that Z' is dissolved in an amont of moisture W_{fC}, which is the soil moisture content at field capacity in the rot zone (in mm or l/m²). W_{fC} can be determined from

$$Wf_C = \frac{W_{fc}}{100} x D \qquad 2.28$$

where,

w = soil moisture content in volume %

f_c = suffix denoting field capacity

D = depth of root zone in mm.

At field capacity the salt concentration (Cf_C) of the soil moisture in the root zone is

$$Cf_C = \frac{Z'}{Wf_C} \qquad 2.29$$

If we consider a period in which Z' changes from Z_1' to Z_2', the average salt concentration $(\overline{C}f_C)$ of the soil moisture at field capacity during that period is $\overline{C}f_C$

$$\overline{C}_{fC} = \frac{Z_1'+Z_2'}{2W_{fC}} = \frac{Z_1'}{W_{fC}} + \frac{\Delta Z'}{2W_{fC}} \qquad 2.30$$

For the salt concentration (C_r) of the water percolating below root zone, the following assuptions can be made each describing a different model:

$$C_r = C_{fc} \qquad 2.31$$

or $\quad C_r = fC_{fc} \qquad 2.32$

or $\quad C_r = fC_{fc} + (1 - f)C_i \qquad 2.33$

where f is the leaching efficiency ($0 < f < 1$).

The following leaching efficiency (f) values have been recommended to be used (Van der Molen, 1973):-

silty loam, sandy loam	f = 0.5 - 0.6
silty clay loam, sandy clay loam, loam	f = 0.4 - 0.5
clay	f = 0.2 - 0.3

2.13 Technique of Water Application for Reclamation

The continuous ponding technique requires a level surface and is relatively inefficient compared with other techniques, such as intermittent ponding or sprinkler irrigation (which does not require a level surface). Flood irrigation results in saturated flow, and the water movement principally occurs in the macropores and at a relatively high velocity. The macropores account for only a small portion of the total porosity of a soil (and only a smal portion of the salt burden contained therin), and salts must diffuse from the smaller micropores to the macropores before they can be flushed from the soil. This diffusion process is slow, and water movement through the profile under saturated flow is too rapid for efficient salt removal. Under unsaturated flow conditions, like those found under sprinkler irrigation, the macropores are still the principal conduit for water flow, however, water in the macropores is in contact with the micropore water for a greater period of time. Thus, there is greater diffusion of salts from the micropores and into the macropores, and greater efficiency of salt removal.

Since the bulk of the soil's salt burden is found in the micropores, sprinkler irrigation is a much more efficient technique for the reclamation of salin soils.

2.14 SYNOPSIS

With this background attempts have been made in the present thesis to (1) derive an expression showing relationship between time and depth of saturation front in the root zone and (2) formulate a mathematical model for predicting the salt concentration with respect to time for sodic soils. The assumption has been made that the soil depth (root zone) under consideration is a thoroughly mixed reservoir and hence the variation in salt concentration with respect to depth has been neglected.

The derivation of the expression as said above and the formulation of model has been described in the next chapter.

CHAPTER-3

LEACHING OF SALTS IN SODIC SOILS

3.0 Introduction

The chapter is comprised of two sections. In the first section, an expression is developed for computation of water infiltered using Green and Ampt equation. In the next section, a mathematical model is developed to find the salt concentration in the root zone depth with respect to time.

3.1 INFILTRATION

Infiltration is the process of water penetrating from the ground surface into the soil. Many factors influence the infiltration rate, including the condition of the soil surface and its vegitative cover, the properties of the soil, such as its porosity and hydraulic cunductivity, and the current moisture content of the soil. Soil strata with different physical properties may overlie each other, forming horizons; for example, a silt soil with relatively high hydraulic conductivity may overlie a clay zone of low conductivity. Also, soils exhibt great spatial variability even within relatively small, areas such as in an agricultural field. As a result of these great spatial variations and the time variations in soil properties that occur as the soil moisture content changes, infiltration is very complex process to be described only approximately with mathematical equations.

The soil water distribution during infiltration into a uniform, relatively dry soil was first presented by Bodman and Coleman (1943). They showed that the profile could be devided into the four zones shown schematically in Fig. 3.1.1. The saturated zone extended from the surface to a maximum depth of approximately 1.5 cm. The transition zone, a region of rapid decrease of soil water content, extended from the zone of saturation to the transmission zone, a zone of nearly constant water content which lengthens as infiltration proceeds. The wetting zone maintains a nearly constant shape during ifltration and culminates in the wetting front which is the visible limit of water penetration into the soil. Except for the saturation and transition zones, the results of Bodman and Colman have been generally confirmed by other investigators. While there has been considerable disagreement in the literature it is generally agreed that, in most cases, the soil will not be completely saturated at the surface due to air entrapment and possible counterflow of the air phase. Most theories of soil water movement do not predict the transition zone. However, McWhorter (1976) showed that an abrupt steepening of the profile near the surface would be predicted for rainfall infiltration if the resistance to air movement is considered.

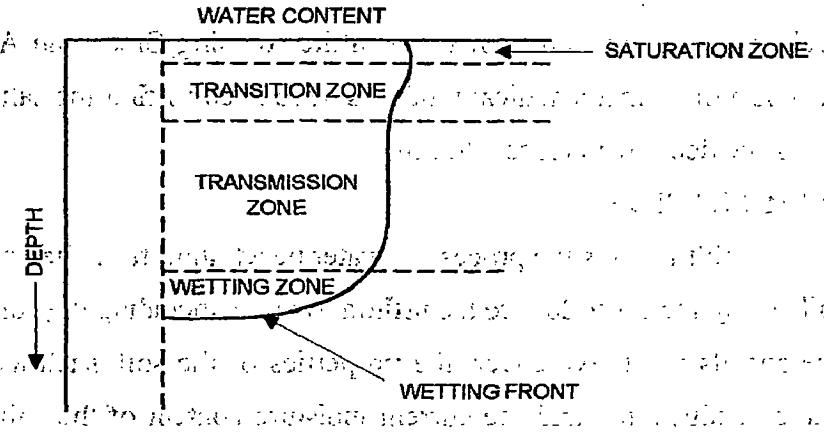
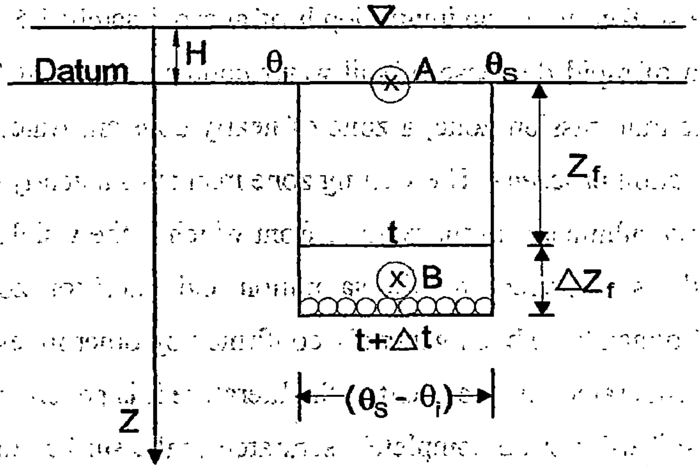


Fig. 3.1.1 Infiltration Zones of Bodman and Colman

3.1.1 Statement of Problem

Let us assume instant ponding. The saturation front is assumed to be abrupt and the water content and K in the saturated zone are assumed to be uniform and constant. Infiltration is thus considered as "piston" flow, as shown below, which is treated with Darcy's equation to obtain equations relating infiltration rate and accumulated infiltration to time since infiltration began.



H is the depth of water above soil surface, Z_f is the depth of saturation front at any time t
θ_s is the natural saturation, and θ_i is initial moisture content.

Piston Flow System

Fig. 3.1.2

Let us consider a saturated mass of soil having thickness ΔZ.

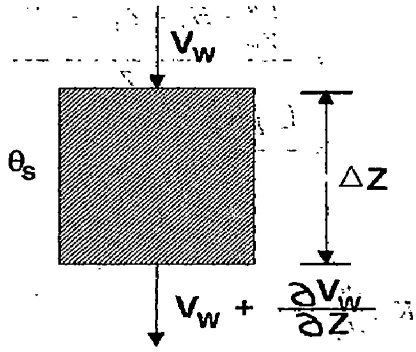


Fig. 3.1.3

In the above figure, V_W is entering velocity and $V_W + \frac{\partial V_W}{\partial Z}.\Delta Z$ is outgoing velocity and $\theta_{(t)} = \theta_{(t+\Delta t)}$, i.e. there is no change in moisture content as it is fully saturated

The mass balance equation is;

Initial storage + Inflow = Final storage + Outflow

Therefore, $\theta_{(t)}.dZ + V_W.\Delta t = \theta_{(t+\Delta t)}.dZ + \left(V_W + \frac{\partial V_W}{\partial Z}.\Delta Z\right)\Delta t$

Thus

$$\frac{\partial V_W}{\partial Z} = 0$$

i.e. velocity is not changing with depth at a particular time.

velocity of water at entering is the infiltration, i.e. I=V

Hydraulic head at point A, $h_A = H + \frac{p_a}{\gamma_w} + 0$

Hydraulic head at point B, $h_B = \frac{p_a}{\gamma_w} - H_c - Z_f \qquad (z \downarrow +ve)$

where, p_a *is air pressure in the miniscus*

H_c *is capillary head,* $H_c = \frac{p_c}{\gamma_w}$

p_c *is capillary pressure*

The hydraulic gradient $\frac{dh}{dZ} = \frac{(h_B - h_A)}{Z_f}$

$$= \frac{\left(\frac{p_a}{\gamma_w} - H_c - Z_f\right) - \left(H + \frac{p_a}{\gamma_w}\right)}{Z_f}$$

$$= \frac{(-H_c - H - Z_f)}{Z_f}$$

From Darcy's law

$$V = -K_s.\frac{dh}{dZ}$$

$$= -\frac{K_s.(-H_c - H - Z_f)}{Z_f}$$

$$= \frac{K_s.(H_c + H + Z_f)}{Z_f}$$

Since I = V,

hence, $I = \frac{K_s.(H_c + H + Z_f)}{Z_f}$ ...3.1.1

This equation is Green & Ampt equation

Using Green and Ampt equation, one can derive the volume of water infiltered in time t. There are generally two situations: in one situation the depth of water is maintained constant from external supply and in other the depth of water varies with time.

3.1.2 Infiltration: When depth H is Maintained Constant

Infiltration during small time dt

$I.dt = dZ_f.(\theta_s - \theta_i)$

where θ_s = *moisture content under natural saturation*

θ_i = *initial moisture content*

Putting $I = \frac{K_s(H_c + H + Z_f)}{Z_f}$

One gets

$$\left[\frac{K_s(H_c+H+Z_f)}{Z_f}\right].dt = dZ_f.(\theta_s-\theta_i)$$

$$\text{or}\quad \frac{K_s}{(\theta_s-\theta_i)}.dt = \frac{Z_f}{H_c+H+Z_f}.dZ_f$$

$$= \frac{H_c+H+Z_f-(H_c+H)}{H_c+H+Z_f}.dZ_f$$

$$\text{or}\quad \frac{K_s}{(\theta_s-\theta_i)}.dt = \left\{1-\frac{H_c+H}{H_c+H+Z_f}\right\}.dZ_f$$

After integration, we get

$$\frac{K_s.t}{\theta_s-\theta_i} = Z_f-(H_c+H)\log_e(H_c+H+Z_f)+A$$

$$at\ t=0,\quad Z_f=0$$

$$Hence,\ A=(H_c+H)\log_e(H_c+H)$$

$$Therefore,\ \frac{K_s.t}{\theta_s-\theta_i} = Z_f-(H_c+H)\log_e(H_c+H+Z_f)+(H_c+H)\log_e(H_c+H)$$

$$= Z_f-(H_c+H)\log_e\left\{\frac{(H_c+H+Z_f)}{(H_c+H)}\right\}$$

$$\text{or}\qquad K_s.t = Z_f(\theta_s-\theta_i)-(\theta_s-\theta_i)(H_c+H)\log_e\left\{\frac{(H_c+H+Z_f)}{(H_c+H)}\right\} \qquad 3.1.2$$

Let the total quantity that infilters be $W_{(t)}$ up to time t. $W_{(t)}$ is given by

$$W_{(t)} = Z_{f(t)}.(\theta_S-\theta_i)$$

$$\text{or}\qquad Z_{f(t)} = \frac{W_{(t)}}{(\theta_S-\theta_i)}$$

Substituting Z_f in (3.1.2)

$$K_s.t = W-(\theta_s-\theta_i)\log_e\left\{\frac{H_c+H+\frac{W}{(\theta_s-\theta_i)}}{H_c+H}\right\}$$

$$\text{or}\quad K_s.t = W-(\theta_s-\theta_i)\log_e\left\{\frac{(\theta_s-\theta_i)(H_c+H)+W}{(\theta_s-\theta_i)(H_c+H)}\right\}$$

$$\text{or}\quad K_s.t = W-(\theta_s-\theta_i)\log_e\left\{1+\frac{W}{(\theta_s-\theta_i)(H_c+H)}\right\} \qquad 3.1(a)$$

At small time in the begining of infiltration $W_{(t)}$ is small. Expanding the logarithmic term and neglecting higher order terms

$$K_s.t = W - (\theta_s - \theta_i)(H_c + H)\left\{\frac{W}{(\theta_s - \theta_i)(H_c + H)} - \frac{W^2}{2(\theta_s - \theta_i)^2 (H_c + H)^2}\right\}$$

$$= \frac{W^2}{2(\theta_s - \theta_i)(H_c + H)}$$

or

$$W = \sqrt{2K_s(\theta_s - \theta_i)(H_c + H)}.\sqrt{t} \qquad 3.1(b)$$

From the above equation, total quantity W can be calculated corresponding to any small time t.

In practice the depth of water on the soil surface changes with time as a certain depth of water is applied in each operation which changes due to infiltration.

3.1.3 Infiltration Under Variable Boundary Head

Let the initial ponding over surface $= \overline{H}$

(i.e. the depth of water applied)

W be the depth of water infiltered in time t

Therefore the depth of water over surface at any time t, $H_{(t)} = \overline{H} - W$

at $t = 0,\ W = 0,\ H_{(t)} = \overline{H}$

From Green & Ampt equation

$$I = \frac{dW}{dt} = \frac{K_s\left[H_{(t)} + H_c + Z_f\right]}{Z_f}$$

$$= \frac{K_s\left[\overline{H} - W + H_c + Z_f\right]}{Z_f}$$

Multiplying the numerator and deno min ator by $(\theta_s - \theta_i)$ *on right hand side*

$$\frac{dW}{dt} = \frac{K_s\left[\left(\overline{H} - W + H_c\right)(\theta_s - \theta_i) + Z_f(\theta_s - \theta_i)\right]}{Z_f(\theta_s - \theta_i)} \qquad \text{...3.1.4}$$

Since $W = Z_f(\theta_s - \theta_i)$

Therefore,

$$\frac{dW}{dt} = \frac{K_s\left[\left(\overline{H} - W + H_c\right)(\theta_s - \theta_i) + W\right]}{W}$$

$$= \frac{K_s\left[\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\}\right]}{W}$$

$$K_s.dt = \frac{W.dW}{\left[\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\}\right]}$$

Multiplying both sides by $\{1 - (\theta_s - \theta_i)\}$

$$\{1 - (\theta_s - \theta_i)\}K_s.dt = \frac{W\{1 - (\theta_s - \theta_i)\}}{\left[\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\}\right]}$$

$$= \frac{\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\} - \left(\overline{H} + H_c\right)(\theta_s - \theta_i)}{\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\}}.dW$$

$$= \left[1 - \frac{\left(\overline{H} + H_c\right)(\theta_s - \theta_i)}{\left(\overline{H} + H_c\right)(\theta_s - \theta_i) + W\{1 - (\theta_s - \theta_i)\}}\right]dW$$

After int *egration we get*

$$\{1 - (\theta_s - \theta_i)\}K_s.t = W - \left(\overline{H} + H_c\right)(\theta_s - \theta_i)\frac{1}{1 - (\theta_s - \theta_i)}\log_e\left\{W[1 - (\theta_s - \theta_i)] + \left(\overline{H} + H_c\right)(\theta_s - \theta_i)\right\} + A$$

At $t = 0,\ W = 0.$ *Hence,*

$$A = \left(\overline{H} + H_c\right)(\theta_s - \theta_i)\frac{1}{1 - (\theta_s - \theta_i)}\log_e\left\{\left(\overline{H} + H_c\right)(\theta_s - \theta_i)\right\}$$

Therefore,

$$\{1 - (\theta_s - \theta_i)\}K_s.t = W - \left(\overline{H} + H_c\right)(\theta_s - \theta_i)\frac{1}{1 - (\theta_s - \theta_i)}\log_e\left\{\frac{W[1 - (\theta_s - \theta_i)] + \left(\overline{H} + H_c\right)(\theta_s - \theta_i)}{\left(\overline{H} + H_c\right)(\theta_s - \theta_i)}\right\} \qquad \text{............. 3.1.5}$$

From the above equation, infiltration W can be estimated for any time t for known values of $\theta_s, \theta_i, K_s, H_c$ *and* $\overline{H}$.

3.1.4 Infiltration in Two Layers of Soil of Different Conductivities K_1 & K_2

Let us consider a soil depth in two layers with conductivities K_1 & K_2. The total depth under consideration being Z_f; the depth of top layer with K_1 conductivity be D_1. Hence the depth of the bottom layer = $Z_f + D_1$.

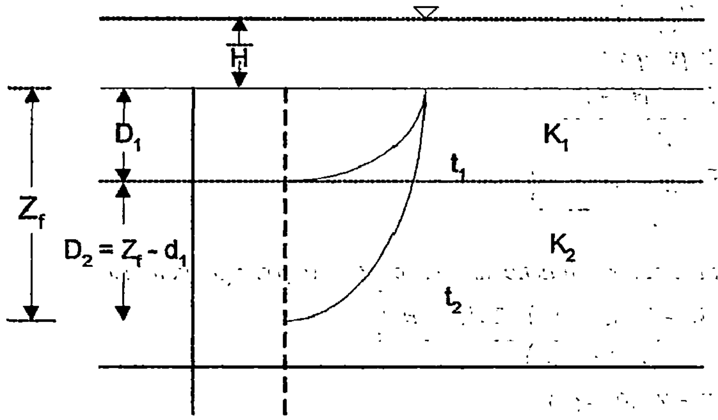


Fig. 3.1.4

In case of a two layers of soil with hydraulic conductivities K_1 and K_2, the resultant conductivity is

$$K_{s(t)} = \frac{D_1+D_2}{\frac{D_1}{K_1}+\frac{D_2}{K_2}} = \frac{D_1+(Z_f-D_1)}{\frac{D_1}{K_1}+\frac{Z_f-D_1}{K_2}} \; ; \; \text{for } Z_f > D_1$$

$$\text{Hence,} \quad K_{s(t)} = \frac{K_1.K_2.Z_f}{D_1K_2+K_1Z_f-D_1K_1}$$

$$\text{For } Z_f < D_1, \quad K_{S(t)} = K_1$$

When the saturation front exceeds the top layer, the infiltration rate, I, is given by

$$I = \frac{dW}{dt} = K_{s(t)}.\frac{[H-W+H_c+Z_f]}{Z_f}$$

$$= \frac{K_1K_2Z_f}{D_1K_2+K_1Z_f-D_1K_1}.\frac{[H-W+H_c+Z_f]}{Z_f}$$

$$= \frac{K_1K_2}{D_1(K_2-K_1)+K_1Z_f}.[H-W+H_c+Z_f]$$

Multiplying numerator and denominator by (θ_S - θ_i) on right hand side,

$$\frac{dW}{dt}=\frac{K_1K_2\left\{\left(\overline{H}-W+H_c\right)(\theta_S-\theta_i)+Z_f(\theta_S-\theta_i)\right\}}{(K_2-K_1)D_1.(\theta_S-\theta_i)+K_1.Z_f.(\theta_S-\theta_i)}\,,$$

Since, $W = Z_f(\theta_S - \theta_i)$ $\qquad$ $(Z_f > D_1)$

and $D_1(\theta_S - \theta_i) = W_1$

Therefore,

$$\frac{dW}{dt}=\frac{K_1K_2\left[\left(\overline{H}-W+H_c\right)(\theta_s-\theta_i)+W\right]}{(K_2-K_1)W_1+K_1W} \qquad 3.1.6$$

$$=\frac{K_1K_2\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_i)+W\{1-(\theta_s-\theta_i)\}\right]}{(K_2-K_1)W_1+K_1.W}$$

or $$K_1K_2dt=\left[\frac{(K_2-K_1)W_1+K_1.W}{\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_i)+W\{1-(\theta_s-\theta_i)\}\right]}\right]dW$$

or $$K_2dt=\left[\frac{\left(\frac{K_2}{K_1}-1\right)W_1+W}{\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_i)+W\{1-(\theta_s-\theta_i)\}\right]}\right]dW$$

Multiplying both sides by $\{1-(\theta_s-\theta_i)\}$ *and after some rearrangement, we get*

$$\{1-(\theta_s-\theta_i)\}K_2dt=\frac{\left(\frac{K_2}{K_1}-1\right)W_1.\{1-(\theta_s-\theta_i)\}+W.\{1-(\theta_s-\theta_i)\}}{\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_i)+W\{1-(\theta_s-\theta_i)\}\right]}dW$$

$$=\left[\frac{\left(\frac{K_2}{K_1}-1\right)W_1.\{1-(\theta_s-\theta_i)\}}{\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_t)+W\{1-(\theta_s-\theta_t)\}\right]}\right]dW$$

$$+\left[1-\frac{\left(\overline{H}+H_c\right)(\theta_s-\theta_i)}{\left[\left(\overline{H}+H_c\right)(\theta_s-\theta_i)+W\{1-(\theta_s-\theta_i)\}\right]}\right]dW$$

After int *egration,*

$$\{1-(\theta_S-\theta_i)\}K_2t=W+\log_e\left[\left(\overline{H}+H_c\right)(\theta_S-\theta_i)+\{1-(\theta_S-\theta_i)\}W\right]\left\{\left(\frac{K_2}{K_1}-1\right)W_1-\frac{\left(\overline{H}+H_c\right)(\theta_S-\theta_i)}{\{1-(\theta_S-\theta_i)\}}\right\}$$

$$+A$$

At $t = t_1$, $\quad W = W_1$

Hence,

$$A=\{1-(\theta_S-\theta_i)\}K_2t_1-W_1-\log_e\left[\left(\overline{H}+H_c\right)(\theta_S-\theta_i)+\{1-(\theta_S-\theta_i)\}W_1\right]x$$

$$\left\{\left(\frac{K_2}{K_1}-1\right)W_1-\frac{\left(\overline{H}+H_c\right)(\theta_S-\theta_i)}{\{1-(\theta_S-\theta_i)\}}\right\}$$

Incorporating A

$$\{1-(\theta_S-\theta_i)\}(t-t_1)=(W-W_1)+\left\{\left(\frac{K_2-K_1}{K_1}\right)W_1-\frac{(\overline{H}+H_c)(\theta_S-\theta_i)}{1-(\theta_S-\theta_i)}\right\}x$$

$$\log_e\frac{(\overline{H}+H_c)(\theta_S-\theta_i)+\{1-(\theta_S-\theta_i)\}W}{(\overline{H}+H_c)(\theta_S-\theta_i)+\{1-(\theta_S-\theta_i)\}W_1}$$

The time t_1 when the saturation front reaches the bottom of the first layer of depth D_1 and time t_2 when the saturation front reaches a Z_f from the surface can be determined using the above relationship.

EXAMPLE

The infiltration rate is obtained for the following soil moisture characteristics:

$\theta_i = 0.290$

$\theta_S = 0.485$

$h_{ci} = 114$ cm

$K_S = 2.88$ cm / hour

$\overline{H} = 10$ cm

Applying Bouwer's method

$$H_c = \int_0^{h_{ci}} k_{rw}(\theta)dh_c$$

$$= 0.75$$

From equation (3.1.5)

$$t = \frac{W - 0.209\log_e(1+4.78W)}{0.0232}$$

The rate of infiltration is presented in Table 3.1.1 and displayed in Chart 3.1.1.

Table 3.1.1

S.N.	W (m)	t (hrs)	Rate of Infiltration (m/hr.)
1	0.01	0.009998	1.000161291
2	0.02	0.038809	0.515350707
3	0.03	0.084822	0.353681242
4	0.04	0.146629	0.272797729
5	0.05	0.222985	0.224230673
6	0.06	0.312787	0.191823622
7	0.07	0.415055	0.168652289
8	0.08	0.52891	0.151254432
9	0.09	0.653564	0.137706498
10	0.099	0.774397	0.127841461
11	0.1	0.788306	0.127841461

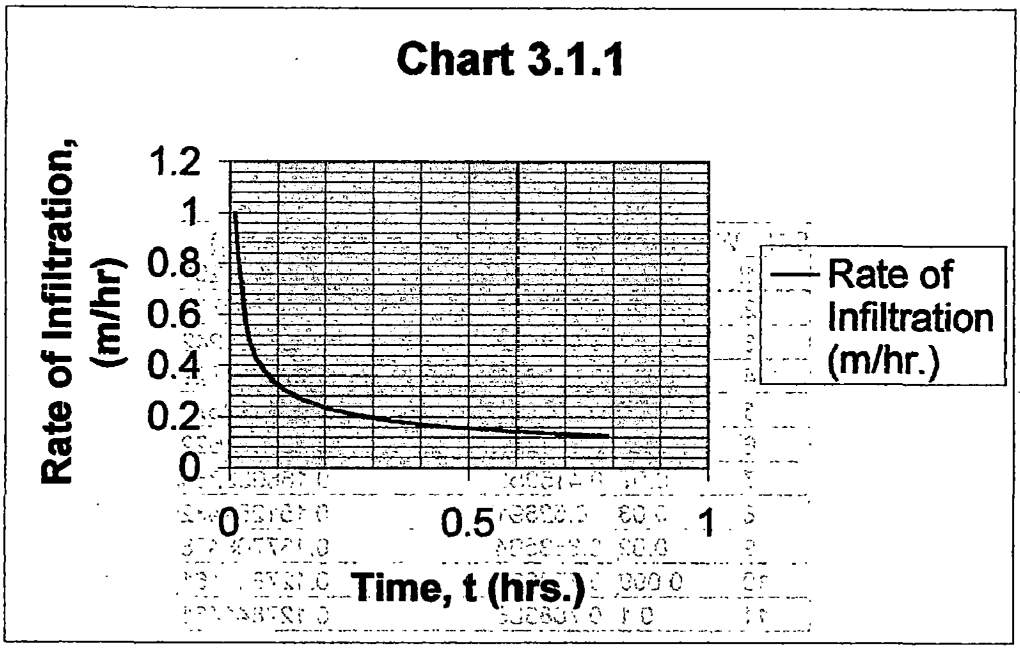


Chart 3.1.1

Verification:

Corresponding to $W = 0.1m$

$$Z_f = \frac{W}{\theta_S - \theta_i} = \frac{0.10}{0.195} = 0.5128m$$

$$\frac{dW}{dt} = \frac{K_S\left[\overline{H} - W + H_c + Z_f\right]}{Z_f} = \frac{W_{11} - W_{10}}{t_{11} - t_{10}}$$

$W_{11} = 0.1m \quad W_{10} = 0.099m \quad t_{10} = 0.774397hr. \quad t_{11} = 0.788300hr.$

Substituting these in above

$$\frac{0.1 - 0.099}{0.788306 - 0.774397} = \frac{0.0288x\left[0.1 - 0.1 + 0.763 + Z_f\right]}{Z_f}$$

or $$\frac{0.001}{0.013909} = \frac{0.0219744 + 0.0288Z_f}{Z_f}$$

or $Z_f = 0.51m.$

For $\overline{H} = 0.20m.$

$\overline{H} + H_c = 0.20 + 0.763 = 0.963m.$

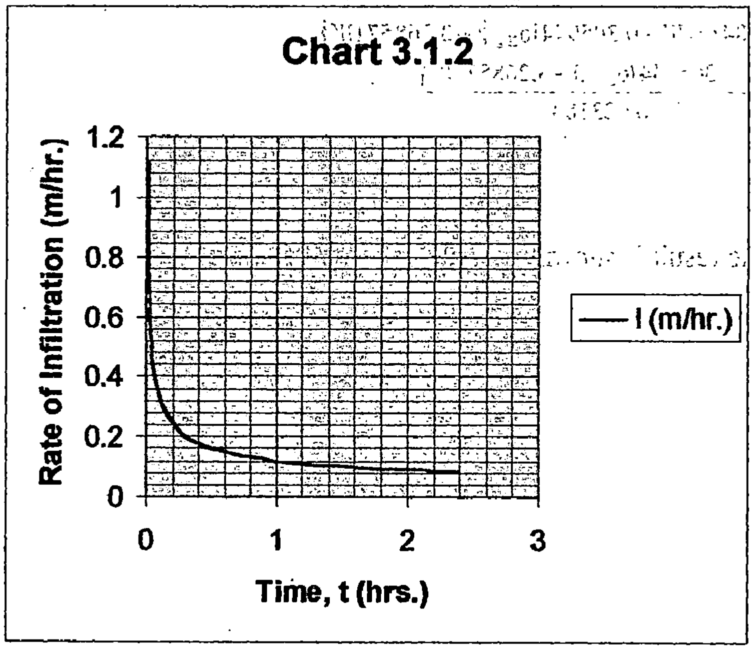
$$\therefore 0.805x0.0288t = W - \frac{0.963x0.195}{0.805}.\log_e\{\frac{0.805W + 0.963x0.195}{0.963x0.195}\}$$

$$\Rightarrow t = \frac{W - 0.2332733\log_e\{1 + 4.2868174W\}}{0.023184}$$

The calculation is shown in Table 3.1.2 and the result is displayed in Chart 3.1.2

Table 3.1.2

1	0.01	0.008989	1.112448
2	0.02	0.034994	0.571522
3	0.03	0.076697	0.391149
4	0.04	0.132927	0.300917
5	0.05	0.202639	0.246744
6	0.06	0.284899	0.210601
7	0.07	0.378863	0.184763
8	0.08	0.483774	0.165367
9	0.09	0.598942	0.150265
10	0.1	0.723743	0.138171
11	0.11	0.857606	0.128264
12	0.12	1.000012	0.119999
13	0.13	1.150484	0.112996
14	0.14	1.308583	0.106986
15	0.15	1.473906	0.10177
16	0.16	1.646081	0.097201
17	0.17	1.824763	0.093163
18	0.18	2.009635	0.089569
19	0.19	2.200399	0.086348
20	0.199	2.376897	0.083723
21	0.2	2.396781	0.083445



Verification

$$at\, t_{20},\ Z_f = \frac{W}{\theta_s - \theta_i} = \frac{0.20}{0.195} = 1.026 \qquad (1)$$

$$\frac{dW}{dt} = \frac{K_s[\overline{H} - W + H_c + Z_f]}{Z_f}$$

$$\frac{W_{21} - W_{20}}{t_{21} - t_{20}} = \frac{K_s[\overline{H} - W + H_c + Z_f]}{Z_f}$$

$$or \quad \frac{0.2 - 0.199}{2.396780992 - 2.376897446}$$

$$= \frac{0.0288[0.763 + Z_f]}{Z_f}$$

$$or \quad 0.050293\, Z_f = 0.0219744 + 0.0288\, Z_f$$

$$or \quad Z_f = 1.0224 \qquad (2)$$

The values from (1) & (2) are practically same.

Let us apply 500 *mm water i.e.* $\overline{H} = 0.50\, m.$

$$\therefore \overline{H} + H_c = 0.50 + 0.763 = 1.263\, m.$$

$$\therefore 0.805x0.0288t = W - \frac{1.263x0.195}{0.805}\log_e\left\{\frac{0.805W + 1.263x0.195}{1.263x0.195}\right\}$$

$$\Rightarrow 0.023184t = W - 0.305944\log_e\{1 + 3.268571W\},$$

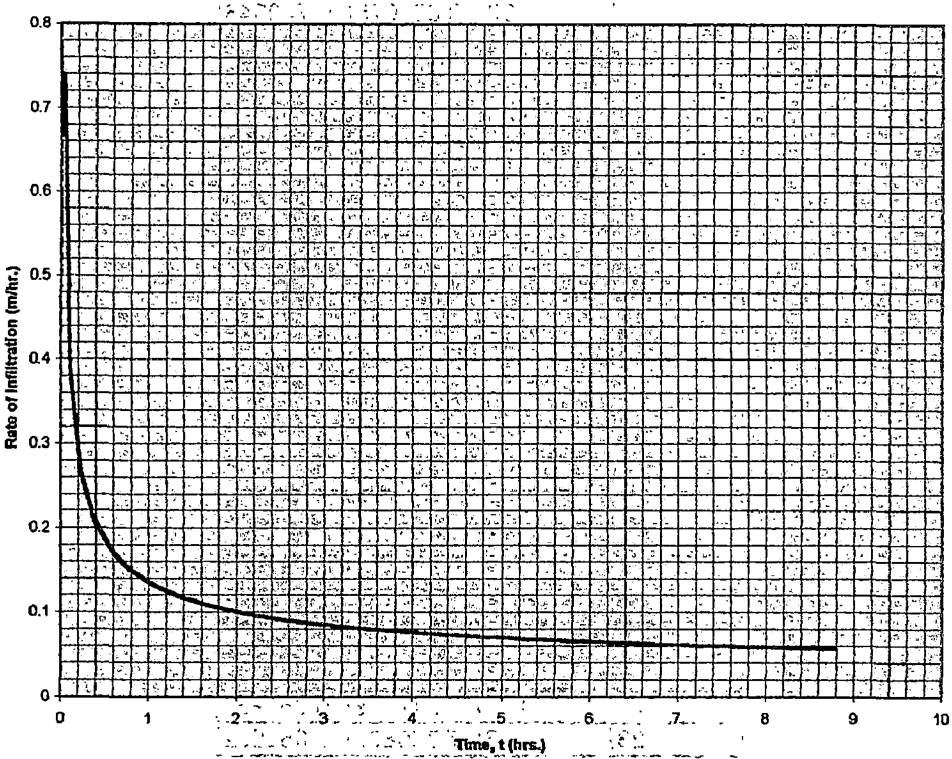
$$\Rightarrow t = \frac{W - 0.305944\log_e\{1 + 3.268571W\}}{0.023184}$$

The result is shown in Table 3.1.3 and Chart 3.1.3

Table 3.1.3

S.N.	W (m.)	t (hrs.)	I (m/hr.)
1	0.02	0.027025	0.740043
2	0.04	0.10383	0.385245
3	0.06	0.224815	0.266886
4	0.08	0.385275	0.207644
5	0.1	0.581222	0.172051
6	0.12	0.809238	0.148288
7	0.14	1.066382	0.131285
8	0.16	1.350095	0.11851
9	0.18	1.658144	0.108555
10	0.2	1.988565	0.100575
11	0.22	2.339623	0.094032
12	0.24	2.709778	0.088568
13	0.26	3.097654	0.083934
14	0.28	3.502021	0.079954
15	0.3	3.921772	0.076496
16	0.32	4.355906	0.073463
17	0.34	4.80352	0.070781
18	0.36	5.263791	0.068392
19	0.38	5.73597	0.066249
20	0.4	6.219372	0.064315
21	0.42	6.71337	0.062562
22	0.44	7.217389	0.060964
23	0.46	7.730897	0.059502
24	0.48	8.253406	0.058158
25	0.499	8.757713	0.056978
26	0.5	8.784462	0.056919

Chart 3.1.3


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Rate of Infiltration (m/hr.)
0
1
2
3
4
5
6
7
8
9
10
Time, t (hrs.)

3.2 RECLAMATION OF SODIC LAND

3.2.1 General

When saline soils are leached during reclamation, or when excess of irrigation water is applied to maintain a low salt content after reclamation, there is always an encroaching fluid whch displaces the salt solution with which it is supposed to be completely miscible. In this chapter, we will consider that depth of root zone which is the problematic zone, and considering it as a single reservoir we will develop a mathematical model to know the salt concentration after leaching.

3.2.2 Statement of the Problem

Solutes are present in the soil in two states, mobile and immobile state. Salt present in immobile solute can be transported only by diffusion. The salt present in mobile solute is transported by advection, dispersion and diffusion. In the present model the effect of dispersion and diffusion is taken into account by assuming the reservoir to be thoroughly mixed reservoir. At a particular time salt concentration varies from one reservoir to other.

Let the concentration of salt in the mobile water be C_m and that in immobile water be C_a, the rate of transfer of salt from immoble water to mobile water, or vice versa, can be given as:

$$\frac{dC_a}{dt} = -K[C_a(t) - C_m(t)] \qquad 3.2a$$

where K is the mass transfer coefficient (day^{-1}). $\frac{dC_a}{dt}$ is the decrease in salt concentration of solute in the immobile region. Fig. 3.2.2 shows the schematic view.

The model assumes that this rate of exchange is proportional to the concentration differance between the two liquid regions (Bolt, G.H.). The mass transfer coefficient is proportional to the molecular diffusitivity of the component in the water, to the total area of the surface of contact between the two fluid phases, and inversly proportional to some length charactrizing the distance between the centroids of the subdomains occupied by the two phases. In principle, this coefficient need not be a constant, although it is often approximated as such, rather than it depends on the saturation of two phases (Bear & Bachmat).

Parker and Valocchi (1986) denoted the transfer coefficient as α^* and suggested that

$$\alpha^* = 15 D\theta_w \frac{1-\frac{\theta_m}{\theta_w}}{r_{im}^2} \qquad ...3.2.b$$

where r_{im} is the radius of spheres of immobile water in their porous medium model, and $\theta_w = \theta_{im} + \theta_m$ where θ_{im} & θ_m are water contents of these two coninua.

With this concept, we will derive for the salt concentration when the saturation front has not crossed the reservoir, and when it has crossed the reservoir. A pictorial view is shown below:

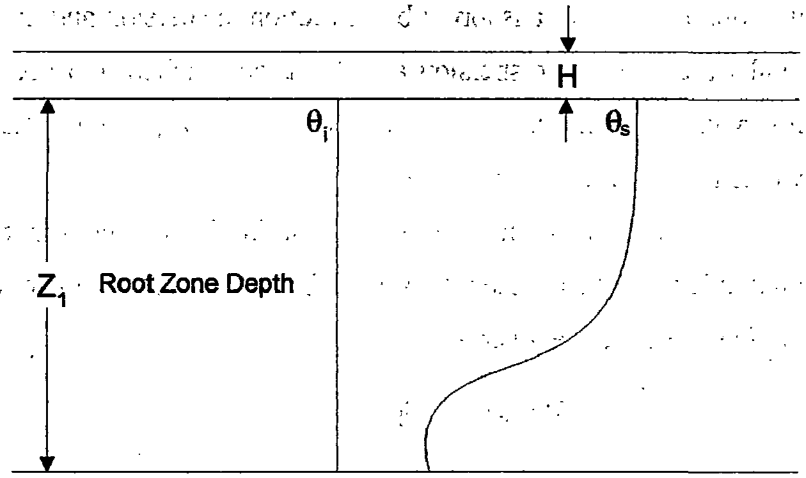


Fig. 3.2.1

3.2.3 Salt Balance, When the Saturation Front has not Crossed the Reservoir

Writing equation 3.2a in finite difference form,

$$\frac{C_a(t+\Delta t)-C_a(t)}{\Delta t} = -K[C_a(t+\Delta t)-C_m(t+\Delta t)]$$

$$or,\ C_a(t+\Delta t)-C_a(t) = -K.\Delta t[C_a(t+\Delta t)-C_m(t+\Delta t)]$$

or,

$$(1+K.\Delta t)C_a(t+\Delta t)-K.\Delta t.C_m(t+\Delta t)=C_a(t) \qquad 3.2.1$$

Now let the irrigation water with salt concentration C_i be applied on the surface of reservoir. Let us assume that within the saturation front the reservoir is a thoroughly mixed reservoir.

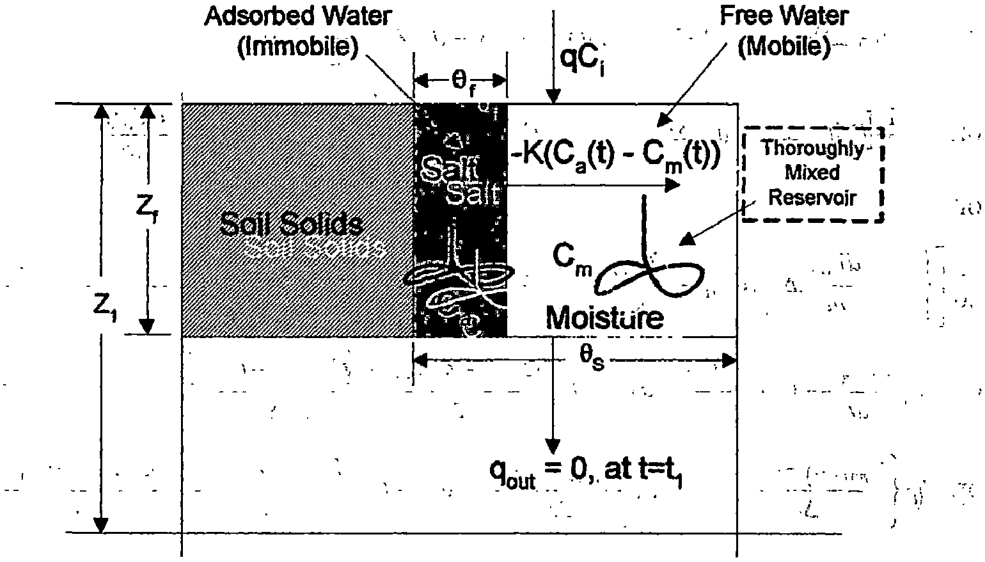


Fig. 3.2.2

For some time after onset of infiltration, the reservoir only receives water and there is no outflow of solute, as the saturation front has not crossed the depth Z_f. Under such situation, the solute volume, $V_{(t)}$, increases with time because of infiltration and it varies with time.

Considering salt balance over a time period of Δt in an initial control volume V(t),

Initial salt mass + (Rate of incoming salt from immobile region). Δt

+ (Rate of incoming salt from irrigation water). Δt

= Final salt mass.

(i) Initial salt mass = $V_{(t)}.C_m(t)$ [V(t) = Volume of mobile water]

(ii) Rate of incoming salt from immobile region = $-\theta_f . Z_f(t)\frac{dC_a(t)}{dt}$

$$\left(\frac{dC_a(t)}{dt} \text{ is negative because } C_a(t+\Delta t)<C_a(t)\right)$$

(iii) Rate of incoming salt from irrigation water = q.Ci

(iv) Final salt mass = $V_{(t+\Delta t)}.C_{m(t+\Delta t)}$

Therefore,

$$V(t)C_m(t)-\theta_f.Z_f.\frac{dC_a(t)}{dt}.\Delta t+q.C_i.\Delta t=V(t+\Delta t)C_m(t+\Delta t)$$

or, $$V(t+\Delta t)C_m(t+\Delta t)-V(t)C_m(t)=q.C_i.\Delta t-\theta_f.Z_f.\frac{dC_a(t)}{dt}.\Delta t$$

or, $$\frac{1}{\Delta t}\left[V(t+\Delta t)C_m(t+\Delta t)-V(t)C_m(t)\right]=q.C_i-\theta_f.\frac{\{Z_f(t)+Z_f(t+\Delta t)\}}{2}.\frac{dC_a(t)}{dt}$$

or,

$$\frac{1}{\Delta t}\left[\left\{V_{(t)}+\frac{dV_{(t)}}{dt}.\Delta t\right\}\left\{C_{m(t)}+\frac{dC_{m(t)}}{dt}.\Delta t\right\}-V_{(t)}.C_{m(t)}\right]=qC_i-\theta_f\frac{\{Z_{f(t)}+Z_{f(t+\Delta t)}\}}{2}.\frac{\{C_{a(t+\Delta t)}-C_{a(t)}\}}{\Delta t}$$

or, $$V_{(t)}.\frac{dC_{m(t)}}{dt}+C_{m(t)}.\frac{dV_{(t)}}{dt}=q.C_i-\theta_f.\frac{\{Z_{f(t)}+Z_{f(t+\Delta t)}\}}{2}.\frac{\{C_{a(t+\Delta t)}-C_{a(t)}\}}{\Delta t}$$

or, $$V_{(t)}\left\{\frac{C_{m(t+\Delta t)}-C_{m(t)}}{\Delta t}\right\}+C_{m(t)}\left\{\frac{V_{(t+\Delta t)}-V_{(t)}}{\Delta t}\right\}=qC_i-\theta_f\left\{\frac{Z_{f(t)}+Z_{f(t+\Delta t)}}{2}\right\}\left\{\frac{C_{a(t+\Delta t)}-C_{a(t)}}{\Delta t}\right\}$$

or,

$$\frac{V_{(t)}}{\Delta t}.C_{m(t+\Delta t)}-\frac{V_{(t)}.C_{m(t)}}{\Delta t}+C_{m(t)}.\left\{\frac{V_{(t+\Delta t)}-V_{(t)}}{\Delta t}\right\}$$
$$=qC_i-\frac{\theta_f\{Z_{f(t)}+Z_{f(t+\Delta t)}\}}{2.\Delta t}.C_{a(t+\Delta t)}+\frac{\theta_f\{Z_{f(t)}+Z_{f(t+\Delta t)}\}}{2.\Delta t}.C_{a(t)}$$

or,

$$\theta_f\left\{\frac{Z_{f(t)}+Z_{f(t+\Delta t)}}{2.\Delta t}\right\}.C_{a(t+\Delta t)}+\frac{V_{(t)}}{\Delta t}.C_{m(t+\Delta t)}$$
$$=qC_i+\frac{2.V_{(t)}.C_{m(t)}}{\Delta t}-\frac{V_{(t+\Delta t)}.C_{m(t)}}{\Delta t}+\frac{\theta_f\{Z_{f(t)}+Z_{f(t+\Delta t)}\}}{2.\Delta t}.C_{a(t)}$$

...3.2.2

Equations 3.2.1 and 3.2.2 give the following matrix:

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ \\ \theta_f.\dfrac{\left\{Z_{f(t)}+Z_{f(t+\Delta t)}\right\}}{2.\Delta t} & \dfrac{V_{(t)}}{\Delta t} \end{bmatrix} \begin{Bmatrix} C_{a(t+\Delta t)} \\ \\ C_{m(t+\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(t)} \\ \\ qC_i+\dfrac{\left\{2V_{(t)}-V_{(t+\Delta t)}\right\}}{\Delta t}C_{m(t)}+\theta_f.\dfrac{\left\{Z_{f(t)}+Z_{f(t+\Delta t)}\right\}}{2.\Delta t}.C_{a(t)} \end{bmatrix} \tag{3.2.2}$$

at t = 0,

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ \\ \theta_f\dfrac{\left\{Z_{f(0)}+Z_{f(\Delta t)}\right\}}{2.\Delta t} & \dfrac{V_{(0)}}{\Delta t} \end{bmatrix} \begin{Bmatrix} C_{a(\Delta t)} \\ \\ C_{m(\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(0)} \\ \\ qC_i+\dfrac{\left\{2V_{(0)}-V_{(\Delta t)}\right\}}{\Delta t}C_{m(0)}+\theta_f\dfrac{\left\{Z_{f(0)}+Z_{f(\Delta t)}\right\}}{2.\Delta t}C_{a(0)} \end{bmatrix}$$

at t = Δt,

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ \\ \theta_f\dfrac{\left\{Z_{f(\Delta t)}+Z_{f(2\Delta t)}\right\}}{2.\Delta t} & \dfrac{V_{(\Delta t)}}{\Delta t} \end{bmatrix} \begin{Bmatrix} C_{a(2\Delta t)} \\ \\ C_{m(2\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(\Delta t)} \\ \\ qC_i+\dfrac{\left\{2V_{(\Delta t)}-V_{(2\Delta t)}\right\}}{\Delta t}C_{m(\Delta t)}+\theta_f\dfrac{\left\{Z_{f(\Delta t)}+Z_{f(2\Delta t)}\right\}}{2.\Delta t}C_{a(\Delta t)} \end{bmatrix}$$

Therefore the equation 3.2.3 can be generalized as:

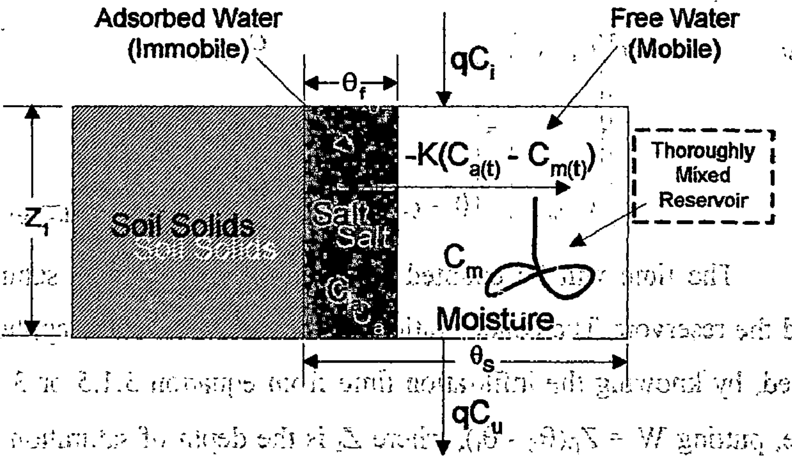
$$\begin{Bmatrix} C_a(n\,\Delta t) \\ \\ C_m(n\,\Delta t) \end{Bmatrix} = \begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix}^{-1} \begin{bmatrix} & & \\ & B & \\ & & \end{bmatrix}$$

where

$$\begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix} = \begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ & \\ \theta_f . \dfrac{\left\{ Z_{f\left(\overline{n-1}\Delta t\right)} + Z_{f(n\,\Delta t)} \right\}}{2.\Delta t} & \dfrac{V_{\left(\overline{n-1}\Delta t\right)}}{\Delta t} \end{bmatrix}$$

$$\begin{bmatrix} & & \\ & B & \\ & & \end{bmatrix} = \begin{bmatrix} C_{a\left(\overline{n-1}\Delta t\right)} \\ \\ qC_i + \dfrac{2V_{\left(\overline{n-1}\Delta t\right)} - V_{(n\,\Delta t)}}{\Delta t} . C_{m\left(\overline{n-1}\Delta t\right)} + \theta_f . \dfrac{\left\{ Z_{f\left(\overline{n-1}\Delta t\right)} + Z_{f(n\,\Delta t)} \right\}}{2.\Delta t} C_{a\left(\overline{n-1}\Delta t\right)} \end{bmatrix}$$

3.2.4 Salt Balance, When the Saturation Front has Crossed the Reservoir



C_u is the salt concentration of effluent

Fig. 3.2.2

When reservoir is filled, salt balance in the mobile region is given by:

$$V.C_{m(t)} - \theta_f.Z_1.\frac{dC_{\bar{a}(t)}}{dt}.\Delta t + q.C_i.\Delta t - q.C_{m(t)}.\Delta t = V.C_{m(t+\Delta t)}$$

$$\text{or,}\quad V.C_{m(t+\Delta t)} = (V - q.\Delta t)C_{m(t)} + q.C_i.\Delta t - \theta_f.Z_1.\frac{\{C_{a(t+\Delta t)} - C_{a(t)}\}}{\Delta t}.\Delta t$$

$$\text{or,}\quad \theta_f.Z_1.C_{a(t+\Delta t)} + V.C_{m(t+\Delta t)} = (V - q.\Delta t)C_{m(t)} + q.C_i.\Delta t + \theta_f Z_1.C_{a(t)}$$

$$\text{or,}\quad \begin{bmatrix} & \\ \theta_f.Z_1 & V \end{bmatrix} \begin{Bmatrix} C_{a(t+\Delta t)} \\ C_{m(t+\Delta t)} \end{Bmatrix} = \begin{bmatrix} \\ (V - q.\Delta t)C_{m(t)} + q.C_i.\Delta t + \theta_f.Z_1.C_{a(t)} \end{bmatrix} \qquad 3.2.5$$

Equation 3.2.1 will also be valid here. Therefore, combining it with equation 3.2.5, we get

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ & \\ \theta_f.Z & V \end{bmatrix} \begin{Bmatrix} C_{a(t+\Delta t)} \\ \\ C_{m(t+\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(t)} \\ \\ (V - q.\Delta t)C_{m(t)} + q.C_i.\Delta t + \theta_f.Z.C_{a(t)} \end{bmatrix} \qquad 3.2.6$$

$V = Z_1.(\theta_S - \theta_i)$

Generalizing the equation 3.2.6 for time steps t = 0, Δt, 2Δt ....(n-1)Δt, we get the equation,

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ & \\ \theta_f.Z_1 & V \end{bmatrix} \begin{Bmatrix} C_{a(n\Delta t)} \\ \\ C_{m(n\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(\overline{n-1}\Delta t)} \\ \\ (V-q.\Delta t)C_{m(\overline{n-1}\Delta t)}+q.C_i.\Delta t+\theta_f Z_1 C_{a(\overline{n-1}\Delta t)} \end{bmatrix} \qquad 3.2.7$$

The time will be counted from the point when the saturation front has crossed the reservoir. The concentration can be known after the applied water is fully infiltered, by knowing the infiltration time from equation 3.1.5 or 3.1.7, as the case may be, putting W = $Z_f.(\theta_S - \theta_i)$, where Z_f is the depth of saturation front. Now, we will take an example.

3.2.4 EXAMPLE

Let us assume initial moisture content of soil $\theta_i = 0.290$ and the moisture is at field capacity. The moisture content at saturation $\theta_S = 0.485$. The hydraulic conductivity of soil $K_S = 0.0288$ m/hour. Let us assume that the depth of problamatic soil Z = 1.0 m. The mass transfer coefficient K = 0.2 per day. Fresh water is applied and the depth of applied water = 0.50 m.

3.2.4.1 CALCULATION

(1) When the Saturation Front has not Crossed the Reservoir

Water infiltered $V_{(n\ \Delta t)}$ and infiltration time is calculated using equation 3.1.5 that are displayed in first and second column of Table 3.2.1. Δt is calculated taking differences of consecutive times and shown in third column of the table. Progressive depth of saturation front is calculated dividing $V_{(n\ \Delta t)}$ by $(\theta_S - \theta_i) = 0.195$ and shown in the fourth column.

Comparing equations 3.2.4 and X, the elements of the matrix are calculated as below:

$$A = 1 + K.\Delta t$$

$$B = -K.\Delta t$$

$$C = \theta_f.\frac{\{Z_{f(\overline{n-1}\Delta t)} + Z_{f(n\Delta t)}\}}{2.\Delta t}$$

$$D = \frac{V_{(\overline{n-1}\Delta t)}}{\Delta t}$$

$$E = C_{a(\overline{n-1}\Delta t)}$$

$$F = \frac{2V_{(\overline{n-1}\Delta t)} - V_{(n\Delta t)}}{\Delta t} C_{m(\overline{n-1}\Delta t)} + C.C_{a(\overline{n-1}\Delta t)} \qquad (C_i = 0, \text{ being fresh water})$$

The values of these elements are entered from fixth to tenth columns ecxept the first row. For the first time step D becomes zero that gives the value of C_m very high tending ti infinity. Hence some manupulation is made for the first time step. The manupulation is that for the first time step, $V_{(\Delta t)}$ is taken as the average of the volumes of that at t = 0 and that at t = Δt. Now, the salt concentrations in mobile and immobile regions are calculated as

$$C_{m(n\Delta t)} = \frac{\begin{vmatrix} E & F \\ A & C \end{vmatrix}}{\begin{vmatrix} B & D \\ A & C \end{vmatrix}}$$

$$C_{a(n\Delta t)} = \frac{E - B.C_{m(n\Delta t)}}{A}$$

When the sturation front reaches 1.0 m. depth, $C_{m(n\Delta t)} = 0.151317$ and $C_{a(n\Delta t)} = 9.844633$. The results are shown in Table 3.2.1

Table3.2.1

$V(n\Delta t)$	Time, t	Δt	$Z_f(n\Delta t)$	A	B	C	D	E	F	$C_m(\Delta t)$	$C_a(\Delta t)$
0.005	0.002	0.002	0.0256	1.000014	-1E-05	2.133	4E-06	10	21.326	8.76239	9.999982
0.01	0.007	0.005	0.0513	1.000043	-4E-05	2.163	0.9697	10	21.633	0.000955	9.999554
0.015	0.015	0.008	0.0769	1.00007	-7E-05	2.197	1.1818	9.9996	21.97	0.001782	9.998852
0.02	0.027	0.012	0.1026	1.000097	-1E-04	2.231	1.2859	9.9989	22.311	0.002867	9.997884
0.025	0.042	0.015	0.1282	1.000123	-1E-04	2.265	1.3541	9.9979	22.653	0.0042	9.996659
0.03	0.06	0.018	0.1538	1.000148	-1E-04	2.3	1.4058	9.9967	22.995	0.005772	9.995185
0.035	0.08	0.021	0.1795	1.000172	-2E-04	2.334	1.4488	9.9952	23.338	0.007575	9.993469
0.04	0.104	0.024	0.2051	1.000195	-2E-04	2.369	1.4865	9.9935	23.681	0.009601	9.991518
0.045	0.13	0.026	0.2308	1.000218	-2E-04	2.403	1.5208	9.9915	24.023	0.011843	9.98934
0.05	0.159	0.029	0.2564	1.000241	-2E-04	2.438	1.5528	9.9893	24.366	0.014292	9.986941
0.055	0.191	0.032	0.2821	1.000262	-3E-04	2.472	1.583	9.9869	24.708	0.016944	9.984328
0.06	0.225	0.034	0.3077	1.000283	-3E-04	2.506	1.6121	9.9843	25.05	0.019789	9.981507
0.065	0.261	0.037	0.3333	1.000304	-3E-04	2.541	1.6402	9.9815	25.392	0.022823	9.978484
0.07	0.3	0.039	0.359	1.000324	-3E-04	2.575	1.6676	9.9785	25.733	0.026038	9.975266
0.075	0.342	0.041	0.3846	1.000343	-3E-04	2.61	1.6944	9.9753	26.075	0.02943	9.971856
0.08	0.385	0.044	0.4103	1.000362	-4E-04	2.644	1.7207	9.9719	26.416	0.032991	9.968262
0.085	0.431	0.046	0.4359	1.00038	-4E-04	2.679	1.7466	9.9683	26.756	0.036717	9.964488
0.09	0.479	0.048	0.4615	1.000398	-4E-04	2.713	1.7723	9.9645	27.097	0.040603	9.960539
0.095	0.529	0.05	0.4872	1.000416	-4E-04	2.748	1.7976	9.9605	27.437	0.044643	9.95642
0.1	0.581	0.052	0.5128	1.000433	-4E-04	2.782	1.8228	9.9564	27.777	0.048832	9.952136
0.105	0.635	0.054	0.5385	1.000449	-4E-04	2.817	1.8477	9.9521	28.117	0.053165	9.947692
0.11	0.691	0.056	0.5641	1.000465	-5E-04	2.851	1.8725	9.9477	28.457	0.057639	9.943091
0.115	0.749	0.058	0.5897	1.000481	-5E-04	2.886	1.8972	9.9431	28.796	0.062248	9.938338
0.12	0.809	0.06	0.6154	1.000497	-5E-04	2.92	1.9217	9.9383	29.135	0.066988	9.933438
0.125	0.871	0.062	0.641	1.000512	-5E-04	2.955	1.9461	9.9334	29.474	0.071855	9.928393
0.13	0.934	0.063	0.6667	1.000527	-5E-04	2.989	1.9704	9.9284	29.812	0.076845	9.923209
0.135	1	0.065	0.6923	1.000541	-5E-04	3.023	1.9947	9.9232	30.15	0.081955	9.917888
0.14	1.066	0.067	0.7179	1.000555	-6E-04	3.058	2.0188	9.9179	30.488	0.087179	9.912435
0.145	1.135	0.069	0.7436	1.000569	-6E-04	3.092	2.0429	9.9124	30.825	0.092516	9.906852
0.15	1.205	0.07	0.7692	1.000582	-6E-04	3.127	2.0669	9.9069	31.162	0.097961	9.901144
0.155	1.277	0.072	0.7949	1.000595	-6E-04	3.161	2.0909	9.9011	31.499	0.103511	9.895314
0.16	1.35	0.073	0.8205	1.000608	-6E-04	3.196	2.1148	9.8953	31.836	0.109163	9.889364
0.165	1.425	0.075	0.8462	1.000621	-6E-04	3.23	2.1387	9.8894	32.172	0.114913	9.883299
0.17	1.501	0.076	0.8718	1.000633	-6E-04	3.265	2.1625	9.8833	32.508	0.120758	9.87712
0.175	1.579	0.078	0.8974	1.000645	-6E-04	3.299	2.1863	9.8771	32.844	0.126697	9.870832
0.18	1.658	0.079	0.9231	1.000657	-7E-04	3.334	2.2101	9.8708	33.179	0.132724	9.864436
0.185	1.739	0.081	0.9487	1.000669	-7E-04	3.368	2.2338	9.8644	33.514	0.138839	9.857936
0.19	1.821	0.082	0.9744	1.00068	-7E-04	3.403	2.2575	9.8579	33.849	0.145037	9.851334
0.195	1.904	0.083	1	1.000691	-7E-04	3.437	2.2812	9.8513	34.183	0.151317	9.844633

(2) When the Saturation Front has Crossed the Reservoir

The calculations are made using equation 3.2.7 and the results are found as below:

$C_{m(n\Delta t)} = 0.328791$, and $C_{a(n\Delta t)} = 9.312389$. The calculations are shown in Table 3.2.2.

Table 3.2.2

$V_{(n\Delta t)}$	Time, t (hrs.)	Δt	q (m/hr.)	A	B	E	F	$C_{m(n\Delta t)}$	$C_{a(n\Delta t)}$
0.2	1.98856496	0.088565	0.100575	1.000735	-0.000735	9.844633	2.883103	0.15499	9.837515
0.21	2.07445808	0.085893	0.098821	1.000713	-0.000713	9.837515	2.881787	0.158498	9.83062
0.21	2.16161497	0.087157	0.09715	1.000723	-0.000723	9.83062	2.880445	0.16201	9.823631
0.22	2.25001125	0.088396	0.095555	1.000734	-0.000734	9.823631	2.879076	0.165523	9.81655
0.22	2.33962324	0.089612	0.094032	1.000744	-0.000744	9.81655	2.877682	0.169034	9.80938
0.23	2.43042794	0.090805	0.092576	1.000754	-0.000754	9.80938	2.876261	0.17254	9.802122
0.23	2.52240299	0.091975	0.091183	1.000763	-0.000763	9.802122	2.874814	0.17604	9.794779
0.24	2.61552665	0.093124	0.089848	1.000773	-0.000773	9.794779	2.873341	0.17953	9.787353
0.24	2.70977779	0.094251	0.088568	1.000782	-0.000782	9.787353	2.871842	0.18301	9.779846
0.25	2.80513585	0.095358	0.08734	1.000791	-0.000791	9.779846	2.870318	0.186476	9.772259
0.25	2.90158082	0.096445	0.08616	1.0008	-0.0008	9.772259	2.868768	0.189928	9.764594
0.26	2.99909325	0.097512	0.085026	1.000809	-0.000809	9.764594	2.867194	0.193364	9.756854
0.26	3.09765418	0.098561	0.083934	1.000818	-0.000818	9.756854	2.865594	0.196782	9.74904
0.27	3.19724518	0.099591	0.082884	1.000827	-0.000827	9.74904	2.86397	0.200181	9.741153
0.27	3.29784828	0.100603	0.081872	1.000835	-0.000835	9.741153	2.862321	0.20356	9.733196
0.28	3.39944597	0.101598	0.080896	1.000843	-0.000843	9.733196	2.860648	0.206917	9.725169
0.28	3.50202123	0.102575	0.079954	1.000851	-0.000851	9.725169	2.858951	0.210251	9.717076
0.29	3.60555742	0.103536	0.079045	1.000859	-0.000859	9.717076	2.85723	0.213562	9.708916
0.29	3.71003836	0.104481	0.078166	1.000867	-0.000867	9.708916	2.855486	0.216849	9.700691
0.3	3.81544827	0.10541	0.077317	1.000875	-0.000875	9.700691	2.853719	0.220111	9.692404
0.3	3.92177174	0.106323	0.076496	1.000882	-0.000882	9.692404	2.851929	0.223346	9.684055
0.31	4.02899376	0.107222	0.075701	1.00089	-0.00089	9.684055	2.850116	0.226555	9.675646
0.31	4.13709969	0.108106	0.074932	1.000897	-0.000897	9.675646	2.84828	0.229737	9.667178
0.32	4.24607523	0.108976	0.074186	1.000904	-0.000904	9.667178	2.846423	0.232892	9.658652
0.32	4.35590643	0.109831	0.073463	1.000912	-0.000912	9.658652	2.844544	0.236018	9.650071
0.33	4.46657968	0.110673	0.072763	1.000919	-0.000919	9.650071	2.842643	0.239116	9.641434
0.33	4.57808169	0.111502	0.072083	1.000925	-0.000925	9.641434	2.840722	0.242185	9.632743
0.34	4.69039946	0.112318	0.071422	1.000932	-0.000932	9.632743	2.838779	0.245224	9.624
0.34	4.80352033	0.113121	0.070781	1.000939	-0.000939	9.624	2.836815	0.248235	9.615205
0.35	4.91743191	0.113912	0.070159	1.000945	-0.000945	9.615205	2.834831	0.251215	9.60636
0.35	5.0321221	0.11469	0.069553	1.000952	-0.000952	9.60636	2.832827	0.254166	9.597466
0.36	5.14757907	0.115457	0.068964	1.000958	-0.000958	9.597466	2.830804	0.257086	9.588524
0.36	5.26379126	0.116212	0.068392	1.000965	-0.000965	9.588524	2.82876	0.259976	9.579535
0.37	5.38074738	0.116956	0.067834	1.000971	-0.000971	9.579535	2.826698	0.262836	9.570499
0.37	5.49843639	0.117689	0.067292	1.000977	-0.000977	9.570499	2.824616	0.265665	9.561419
0.38	5.61684747	0.118411	0.066763	1.000983	-0.000983	9.561419	2.822516	0.268464	9.552295
0.38	5.73597006	0.119123	0.066249	1.000989	-0.000989	9.552295	2.820397	0.271233	9.543127

0.39	5.85579383	0.119824	0.065747	1.000995	-0.000995	9.543127	2.818261	0.273971	9.533918
0.39	5.97630866	0.120515	0.065258	1.001	-0.001	9.533918	2.816106	0.276679	9.524668
0.4	6.09750467	0.121196	0.064781	1.001006	-0.001006	9.524668	2.813934	0.279356	9.515377
0.4	6.21937216	0.121867	0.064315	1.001012	-0.001012	9.515377	2.811744	0.282003	9.506047
0.41	6.34190167	0.12253	0.063861	1.001017	-0.001017	9.506047	2.809538	0.28462	9.496678
0.41	6.4650839	0.123182	0.063418	1.001022	-0.001022	9.496678	2.807314	0.287206	9.487272
0.42	6.58890977	0.123826	0.062985	1.001028	-0.001028	9.487272	2.805074	0.289763	9.477829
0.42	6.7133704	0.124461	0.062562	1.001033	-0.001033	9.477829	2.802818	0.29229	9.46835
0.43	6.83845705	0.125087	0.062149	1.001038	-0.001038	9.46835	2.800546	0.294787	9.458835
0.43	6.96416121	0.125704	0.061745	1.001043	-0.001043	9.458835	2.798258	0.297254	9.449287
0.44	7.0904745	0.126313	0.06135	1.001048	-0.001048	9.449287	2.795954	0.299692	9.439704
0.44	7.21738873	0.126914	0.060964	1.001053	-0.001053	9.439704	2.793635	0.3021	9.430089
0.45	7.34489588	0.127507	0.060586	1.001058	-0.001058	9.430089	2.791302	0.30448	9.420441
0.45	7.47298807	0.128092	0.060217	1.001063	-0.001063	9.420441	2.788953	0.30683	9.410762
0.46	7.60165758	0.12867	0.059855	1.001068	-0.001068	9.410762	2.78659	0.309152	9.401053
0.46	7.73089687	0.129239	0.059502	1.001073	-0.001073	9.401053	2.784213	0.311446	9.391313
0.47	7.86069851	0.129802	0.059155	1.001077	-0.001077	9.391313	2.781821	0.313711	9.381544
0.47	7.99105522	0.130357	0.058816	1.001082	-0.001082	9.381544	2.779416	0.315947	9.371746
0.48	8.1219599	0.130905	0.058483	1.001087	-0.001087	9.371746	2.776997	0.318156	9.361919
0.48	8.25340552	0.131446	0.058158	1.001091	-0.001091	9.361919	2.774565	0.320338	9.352066
0.49	8.38538525	0.13198	0.057839	1.001095	-0.001095	9.352066	2.77212	0.322492	9.342185
0.49	8.51789233	0.132507	0.057526	1.0011	-0.0011	9.342185	2.769661	0.324619	9.332279
0.5	8.65092018	0.133028	0.057219	1.001104	-0.001104	9.332279	2.767191	0.326718	9.322346
0.5	8.7844623	0.133542	0.056919	1.001108	-0.001108	9.322346	2.764707	0.328791	9.312389

Now, suppose after stopping the water supply, the water content of the soil remains higher than the field capacity for ten days. The soil is left for exchange of salt concentrations from immobile region to mobile region. q will be zero and equation 3.2.7 will be changed to:

$$\begin{bmatrix} 1+K.\Delta t & -K.\Delta t \\ \\ \theta_f.Z & V \end{bmatrix} \begin{Bmatrix} C_{a(n\Delta t)} \\ \\ C_{m(n\Delta t)} \end{Bmatrix} = \begin{bmatrix} C_{a(\overline{n-1}\Delta t)} \\ \\ V.C_{m(\overline{n-1}\Delta t)}+\theta_f.Z.C_{a(\overline{n-1}\Delta t)} \end{bmatrix}$$

Making $\Delta t = 1$ day, K = 0.2 per day

A = 1.2

B = -0.2

C = 0.29

D = 0.195

$E = C_{a(\overline{n-1}\Delta t)}$

$F = 0.195.C_{m(\overline{n-1}\Delta t)} + 0.29.C_{a(\overline{n-1}\Delta t)}$

The calculations are shown in Table 3.2.2 and the results are found as below:

$C_{m(\overline{n}\Delta t)} = 5.605684$

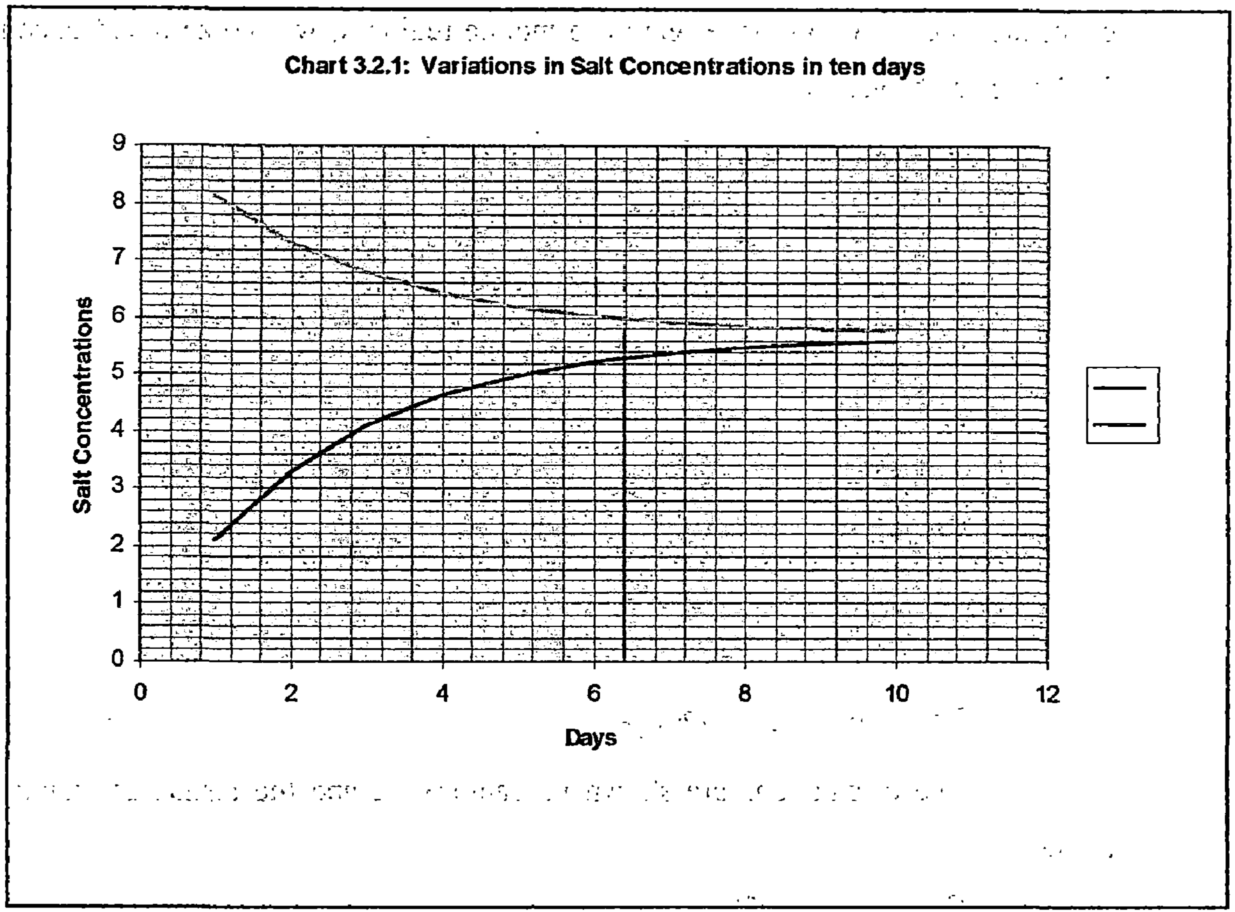
$C_{a(n\Delta t)} = 5.76155$

Table 3.2.3

Exchange in Salt Concentrations for ten days

E	F	Day	$C_{m(n\Delta t)}$	$C_{a(n\Delta t)}$
9.312389	2.764707	1	2.113205	8.112525
8.112525	2.764707	2	3.304853	7.311246
7.311246	2.764708	3	4.100646	6.776146
6.776146	2.764708	4	4.632083	6.418802
6.418802	2.764709	5	4.986982	6.180166
6.180166	2.76471	6	5.223987	6.020803
6.020803	2.76471	7	5.382262	5.914379
5.914379	2.764711	8	5.487959	5.843309
5.843309	2.764712	9	5.558546	5.795849
5.795849	2.764712	10	5.605684	5.764155

The variations in salt concentrations during these ten days are shown in chart 3.2.1



The red curve is $C_{a(n\Delta t)}$ and the blue curve is $C_{m(n\Delta t)}$.

Chart 3.2.1 shows that the rate of increase in salt concentration of $C_a(n\Delta t)$ is more than the rate of decrease in the concentration of $C_m(n\Delta t)$. This is because the volume of the immobile water is more than the volume of mobile water. Let us have a test checking taking $\theta_S = 0.40$ and $\theta_i = 0.20$ so that volume in both regions equal the calculation is made and the result is displayed in Chart 3.2.1 a:

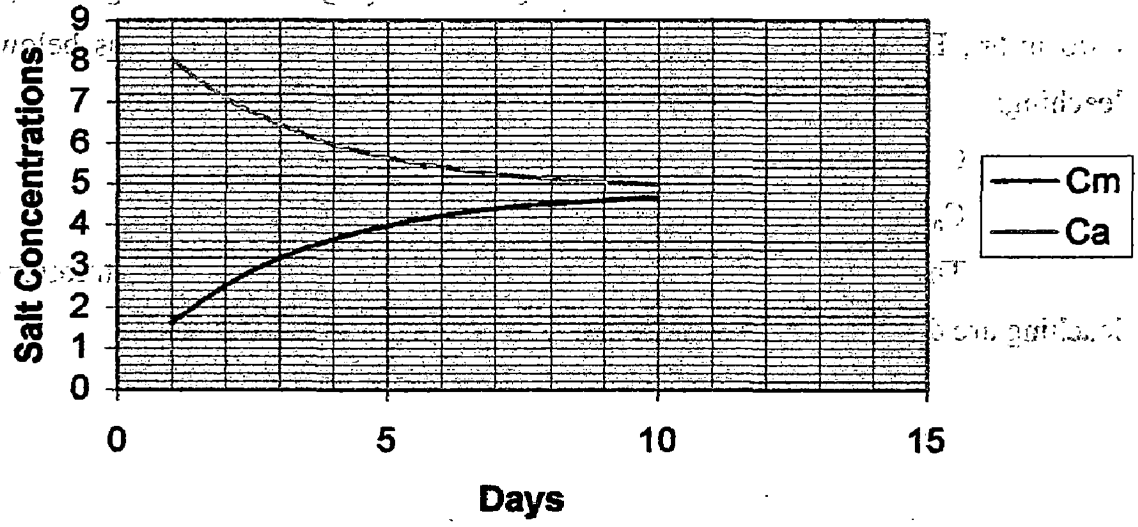


Chart 3.2.1 a:Exchange of salt in same proportion

It is clear from Chart 3.2.1 a that C_a and C_m both are converging to a middle value.

Now let us see the variation in the rate of exchange and the difference in concentrations with time. The result is shown in Chart 3.2.1 b conforming to Table 3.2.3.

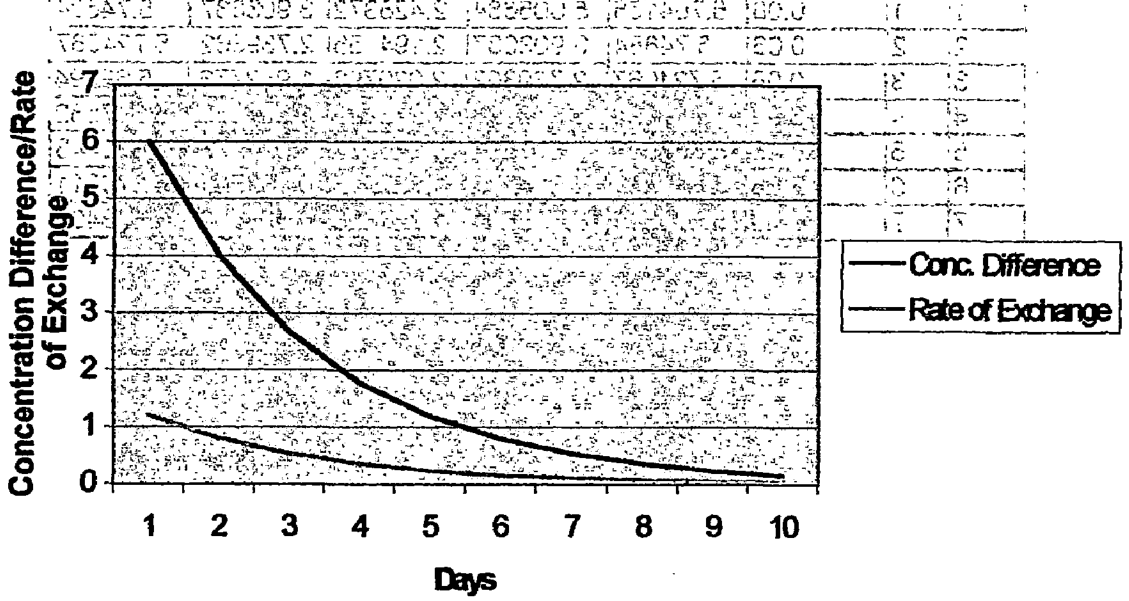


Chart 3.2.1 b

Now, again after applying 0.50 m. water and neglecting the exchange during the time when reservoir is being filled, because the difference in salt concentrations in mobile and immobile regions is negligible, and taking average q as 0.06 m/hr., Equation 3.2.7 shall be applied and the result is found as below after leaching:

$C_m = 0.593083$

$C_a = 5.538464$

The calculations are shown in Table 3.2.4 and the salt concentrations after leaching are displayed on Chart 3.2.2

Table 3.2.4

Reduction in Salt Concentrations

S.N.	$n\,\Delta t$	q = l	E		F	$C_{m\,(n\,\Delta t)}$	$C_{a\,(n\,\Delta t)}$
	hrs.	m/hr.	$C_{a\,(\overline{n-1}\,\Delta t)}$	$C_{m\,(\overline{n-1}\,\Delta t)}$		Cm	Ca
1	1	0.06	5.764155	5.605684	2.428372	3.903637	5.74884
2	2	0.06	5.74884	3.903637	2.194155	2.739362	5.724067
3	3	0.06	5.724067	2.739362	2.029793	1.942773	5.69294
4	4	0.06	5.69294	1.942773	1.913227	1.397582	5.657582
5	5	0.06	5.657582	1.397582	1.829372	1.024278	5.619443
6	6	0.06	5.619443	1.024278	1.767916	0.768501	5.579511
7	7	0.06	5.579511	0.768501	1.721806	0.593083	5.538464

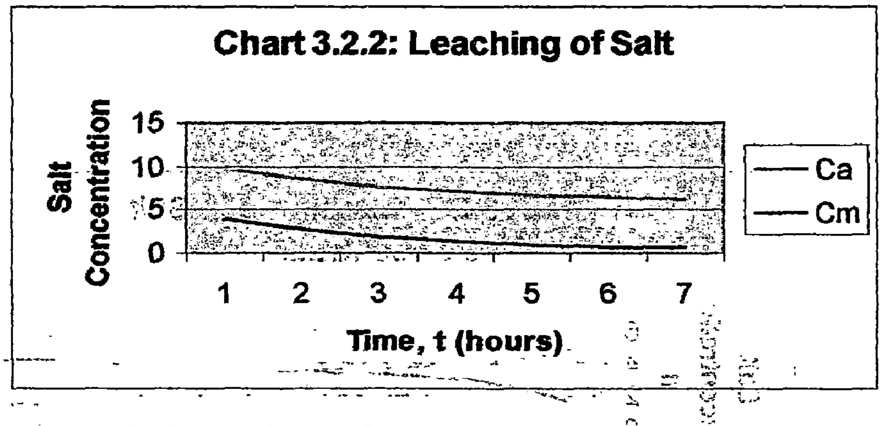


Chart 3.2.2: Leaching of Salt

Now, again the soil is left for exchange for ten days and the result of exchange after ten days is found as below:

$C_{m(n\Delta t)} = 3.497961$

$C_{a(n\Delta t)} = 3.585197$

The calculations are shown in Table 3.2.5 and the exchange of salt concentrations are displayed in Chart 3.2.3.

Table 3.2.5

Exchange in Salt Concentrations for ten days

			$C_{m(n\Delta t)}$	$C_{a(n\Delta t)}$
E	**F**	Day	**Cm**	**Ca**
5.538464	1.721806	1	1.575386	4.877951
4.877951	1.721806	2	2.231376	4.436855
4.436855	1.721806	3	2.669452	4.142288
4.142288	1.721807	4	2.962003	3.945574
3.945574	1.721807	5	3.157372	3.814207
3.814207	1.721807	6	3.287841	3.726479
3.726479	1.721808	7	3.374969	3.667894
3.667894	1.721808	8	3.433155	3.628771
3.628771	1.721809	9	3.472012	3.602644
3.602644	1.721809	10	3.497961	3.585197

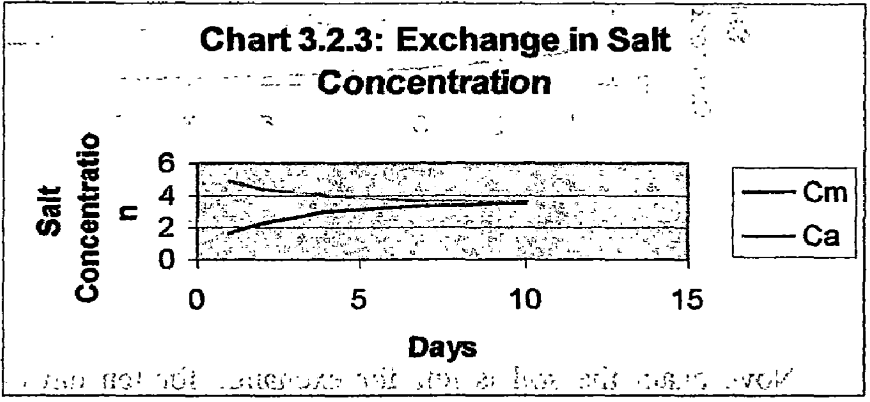


Chart 3.2.3: Exchange in Salt Concentration

Now, again the leaching of salt is made with 0.50 m. water and the result is found as below:

$C_{m(n\Delta t)} = 0.369685$ (say, 0.37)

$C_{a(n\Delta t)} = 3.445003$ (say, 3.45)

The calculations are shown in Table 3.2.6 and the result is displayed in Chart 3.2.4. At this stage, we get the total salt concntration as 3.82 m mhos/ cm. which is in safe limit i.e. less than 4.0 m mhos/ cm. Thus the total leaching requirement comes out to 1.50 m.

Table 3.2.6
Reduction in Salt Concentrations

S.N.	$n\Delta t$	q = I	E		F	$C_{m(n\Delta t)}$	$C_{a(n\Delta t)}$
	hrs.	m/hr.	$C_{a(\overline{n-1}\Delta t)}$	$C_{m(\overline{n-1}\Delta t)}$		Cm	Ca
1	1	0.06	3.585197	3.497961	1.511932	2.435739	3.575735
2	2	0.06	3.575735	2.435739	1.365788	1.709133	3.56037
3	3	0.06	3.56037	1.709133	1.26324	1.211995	3.541039
4	4	0.06	3.541039	1.211995	1.190521	0.871752	3.519066
5	5	0.06	3.519066	0.871752	1.138216	0.638781	3.495356
6	6	0.06	3.495356	0.638781	1.099889	0.479158	3.470528
7	7	0.06	3.470528	0.479158	1.071139	0.369685	3.445003

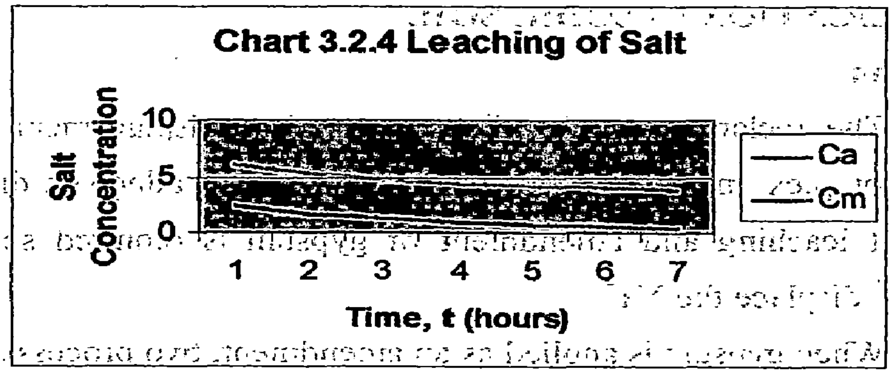


Chart 3.2.4 Leaching of Salt

3.2.5 APPLICATION IN SODIC SOIL

Introduction

The reclamation of sodic soil requires displacement of Na^+ from the exchange complex and leaching of displaced Na^+. An adequate drainage is required for efficient leaching and amendment of gypsum is required so that the divalent cations Ca^{2+} displace the Na^+.

When gypsum is applied as an amendment, two processes are involved:

1. Solubility of gypsum in water
2. Cation Exchange Reaction

As far as solubility of gypsum is concerned, if it is fresh water, the solubility is 100%. If it is saline water, solubility is increased. The details of solubility of gypsum is shown on Appendix-II.

With respect to the rate of Cation Exchange Reaction it may be stated that at least under favourable conditions, this rate is very high (half-time of reaction is a matter of minutes or even less) - (Bolt, G.H.)

We may therefore assume that the two processes are instanteneous.

The total amount of cations held exchangeably by a unit mass (weight) of soil is termed the Cation Exchange Capacity of the soil, CEC. Out of it, the percentage of sodium exchangeable is termed as Exchangeable Sodium Percentage, ESP. The gupsum requirement is based on the ESP. Suppose ESP = 30 and CEC = 100. The target would be to reduce ESP to 10 that is in safe limit. Then the Exchangeable Sodium will be $\frac{(30-10)x100}{100} = 20\, mol / Kg \; of \; soil.$ Based on this exchangeable sodium, the gypsum requirement is calculatad (Appendix-I). This means the gypsum so calculated would release 20 mol of Na^+ per Kg of soil that has to be leached out.

Statement of the Problem

The salt present in the immobile region includes the adsorbed salt as well as free salt, that is in liquid phase. As stated above, the gypsum requirement is calculated as per Appendix-I and the concentration of adsorbed salt, the portion that has to be leached out, can be calculated and adding with the concentration of free salt present in the immobile region will give the total salt concentration. Since the concentration of adsorbed salt is in mol per unit weight and that of free salt in liquid phase is in mol per unit volume,

Total Concentration = $\rho.C_{ads} + \theta_f.C_l$

Where, C_{ads} is the adsorbed salt concentration.

ρ is the bulk density of soil.

C_l is the salt concentration in liquid phase.

When gypsum is applied in three phases, one third in each phase, only one third of adsorbed salt concentration will be taken into account for calculation. And the gypsum applied in each phase shall be counted as salt concentration in the mobile region. As done in the previous section, the salt concentration after leaching can be assessed and the leaching requirement can be known.

Some Important Conversions & Relationships

1 mmhos cm^{-1} (cgs unit) = 1 dS m^{-1} (SI unit)

1 meq/litre = 12 mmhos cm^{-1} at 25^0 C

where, meq/litre is the concentration (C) of soil solution

and mmhos cm^{-1} is the Electrical Conductivity (EC) of soil solution.

EC (dS m^{-1}) x 10 = C ($mmol_c$ L^{-1}) [sum of dissolved cation (or anion) charge]

EC (dS m^{-1}) x 640 = Total Dissolved Salt (mg L^{-1})

EC (dS m^{-1}) x 0.40 = τ_0 (bars) [osmotic pressure at 25^0 C]

Concentration in mg/litre = Equivalent Weight x Concentration in meq/litre

Equivalent Weight of Na = 23, Mg = 12 & Ca = 20

3.2.6 LIMITATIONS

This model assumes uniform concentration throughout the depth where as the salt concentration varies with depth. However, for the small depth, this mathematical model can fit well. In general, the top 0.25 to 0.30 m layer of soil becomes sodic and exhibits the bad structure.

CHAPTER-4

IMPACT OF RECLAMATION OF SODIC LAND
ON
GROUND WATER QUALITY

4.1 Introduction

The most important phenomenon taking into the soil matrix is that cation exchange makes it possible that ions, that are brought into the system via the solution phase, are retained by the soil (e.g. K-ions from fertilizer salts, NH_4-ions from fertilizers or other sources, Na-ions from waste water etc.). In such a case the cations which were held originally by the solid phase are exchanged and released into the soil solution. As a rule the adsorption of cations is a beneficial characteristic of the soil system that provide nuetrients to the crops. At the same time unwanted polluting cations may be retained in the soil instead of being passed on to the groundwater. However, excessive adsorption of unwanted cations could disturb the soil system as a biotope. The adsorption of Na-ions is the special case here in the present topic.

Therefore, when sodic land is reclaimed, the salt goes into the groundwater and we are bound to compromise with the groundwater quality. Keeping this in mind, the reclamation is made only upto the extent that SAR of the soil may get reduced to 10 that is tolerable. On the other hand, every effort is made to have proper drainage so that the salt may not go into the ground water.

While reclamation is done in a wide area, there should be monitoring of its impact on ground water quality. A study is presented here that is based on the report of Remote Sensing Application Centre, Uttar Pradesh, Lucknow.

4.2 Background of Report

The Environment Management Plan of U.P. Sodic Land Reclamation Project envisages a continuous monitoring of ground water and surface water to study the effect of reclamation process on the quality of water. Ground water studies have two components one general ground water monitoring and the other detailed ground water monitoring. This report deals with the detailed ground water monitoring components.

Under this components of study, two piezometer clusters comprising a total of 10 piezometers at each site have been constructed at Hardoi and Raebareli in 1995 & 1996 respectively at varing depths in Phase -I. Deepest piezometer is centrally located and a Automatic Water Level Recorder (AWLR) was installed in 1996 for continuous water level monitoring at both sides. Piezometers were constructed at depths of 2, 4, 6, 8, 10, 12, 18, 24, 30 and 32 m bgl.

Location of one Piezometer cluster in Hardoi reclamation has been constructed in village Ramalwa of Sandila block. Other piezometer cluster site is located at village Baikhara (Chandu Ka Purwa), block of Amawan of Raebareli district.

In Hardoi reclamation area, piezometer cluster was constructed in October, 1995 and Automatic Water Level Recorder (AWLR) was installed in deepest piezometer in December 1996. Piezometer cluster in Raebareli reclamation area was constructed in April 1996 and Automatic Water Level Recorder (AWLR) was installed in December 1996. In Phase-II, under Detailed water monitoring components, three piezometer clusters have been constructed in village Ainthoo, Pratapgarh, village Kharra Nagla, Manipuri and village Barhin, Auraiya districts. The each cluster consists of 4 piezometers installed at the depth of 3, 5, 10 and 15 m bgl.

4.3 Assessment of Ground Water

4.3.1 Ground Water Level

In the reclamation year 2000, the ground water quality level and quality monitoring was made thrice in the year i.e. pre monsoon, post monsoon and post rabi at three piezometer clusters site of Kharra Nagla (Manipuri), Barhin (Auraiya) and Ainthoo (Pratapgarh). The ground water level was recorded during pre monsoon 2002 as: 5.50-5.60 m bgl at Barhin, 3.70-3.90 m bgl at Kharra Nagla and 0.65 m bgl at Ainthoo whereas during post monsoon period water level recorded at Barhin is 5.10-5.20 m bgl, at Kharra Nagla 3.10 to 3.20 m bgl and at Ainthoo 0.50 m bgl. The water level is measured during post rabi period (March, 2002) are: at Barhin 4.90-5.10 m bgl and at Kharra Nagla 3.20 m bgl and at Ainthoo 0.65-0.70 m bgl. The seasonal trend of water level shows response to the precipitation received during the year 2002 in the respective areas. The water levels recorded in Kharra Nagla cluster show potential water logged conditions. In Pratapgarh cluster site water level is very shallow ranging below 1.00 m bgl in all the three periods. Relevant chemical parameters analysed are given in Table 4.2. The data for Phase-I is also shown in Table 4.1.

4.3.2 Ground Water quality

Depth-wise variation in different chemical parameters are as follows :-

i. pH ranges from 7.2 to 8.9 during pre monsoon period with maximum at deeper depth of 10.60 m. In post monsoon period, pH ranged from 7.9 to 8.8 and during post rabi period, pH was found ranging from 8.2 to 10.0 with highest 10.0 at middle depth of 10.60 m at Kharra Nagla (Manipuri). pH shows increasing trend with depth upto 11 m and than again show decreasing trend upto the deepest depth of 3.2 m.
ii. EC values generally range 490 to 4960 µS/cm during pre monsoon. The highest values of 4960 µS/cm and 3690 µS/cm found in the cluster site of Kharra Nagla (Manipuri) whereas in other four cluster sites EC ranges below 750 µS/cm. During post monsoon 2002 EC values ranged from 413 to 1290 µS/cm and in the post rabi it ranged from 382 to 1375 µS/cm. EC values generally show decreasing trend with depth.
iii. SO_4 concentration is highest (750 meq/l) at 6.00 m depth and shows decreasing trend with depth at few places and/or no definite trend in clay lithosection possibly of very poor hydraulic conductivity.
iv. HCO_3 ranges between 1.60 to 21.80 meq/l with highest value at 6.00 m depth in the clayey zone.
v. RSC values range from negative to 2.17 meq/l being highest at deeper depth.

4.3.3 ASSESSMENT OF GROUND WATER QUALITY FOR IRRIGATION AND POTABLE PURPOSES

One of the objectives of detailed ground water monitoring is to analyse health hazards associated with the dissolved solids. Different chemical parameters determining quality of potable water are given in Table 2. A perusal of table shows that concentration of different parameter found in the study area falls well within the permissible limits. So there is no health hazards associated with the dissolved solids. Most of the values of EC, SAR falls in the C_2S_1 class indicating moderate salinity hazard, but samples collected during monsoon period falls in C_3S_1 class indicates high salinity, which may be due to addition of salts from ground water recharge. However, since they fall in C_3S_1 category analysis shows low sodicity hazard and medium salinity hazard. As per U.S. Salinity diagram classification there is no significant deterioration in irrigation water quality after inception of reclamation program in the area.

The U.S. Salinity diagram classifications for different district are shown from Fig. 4.1 to Fig. 4.17.

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District :ALIGARH

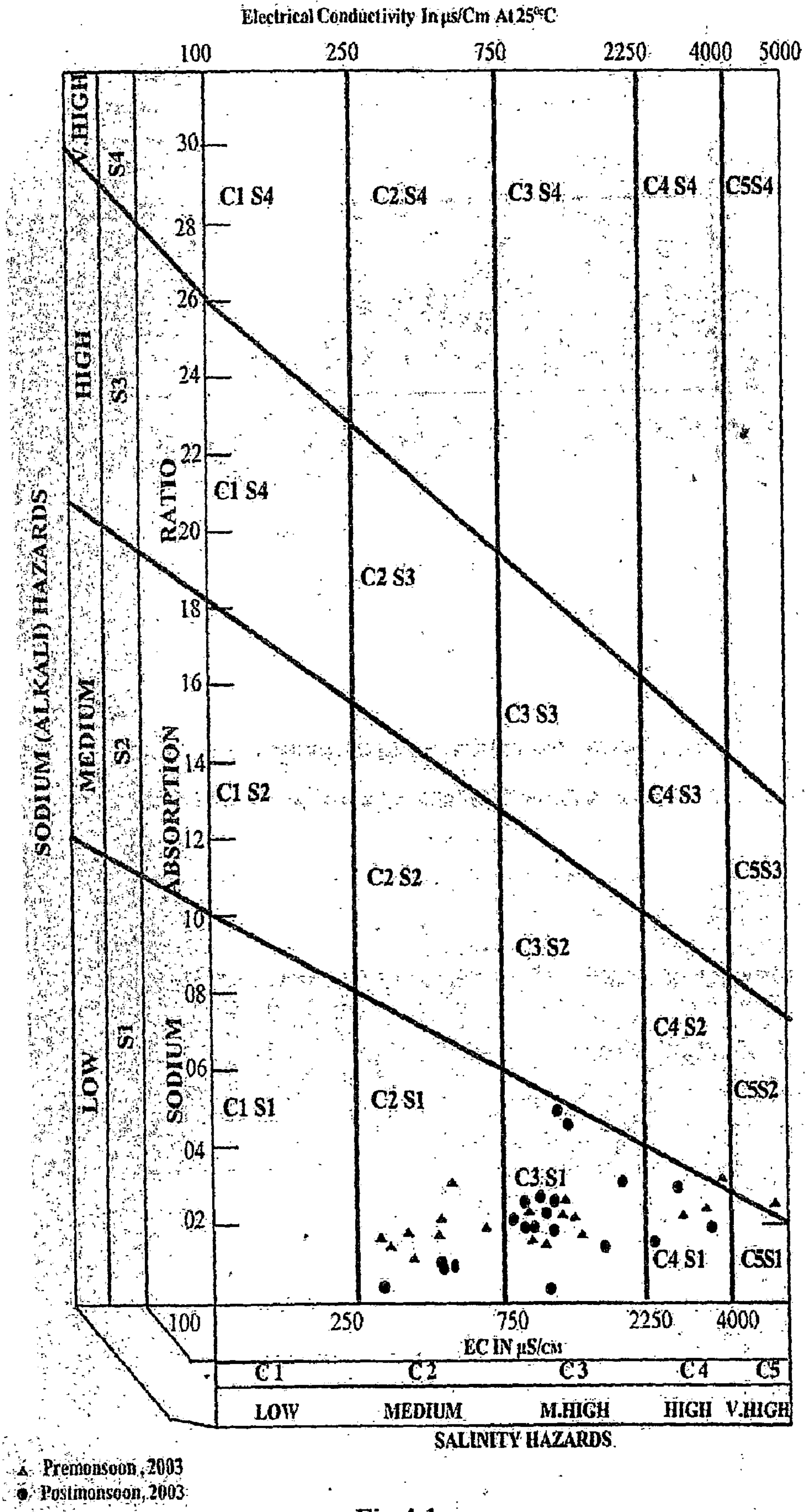


Fig 4.1

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : PRATAPGARH

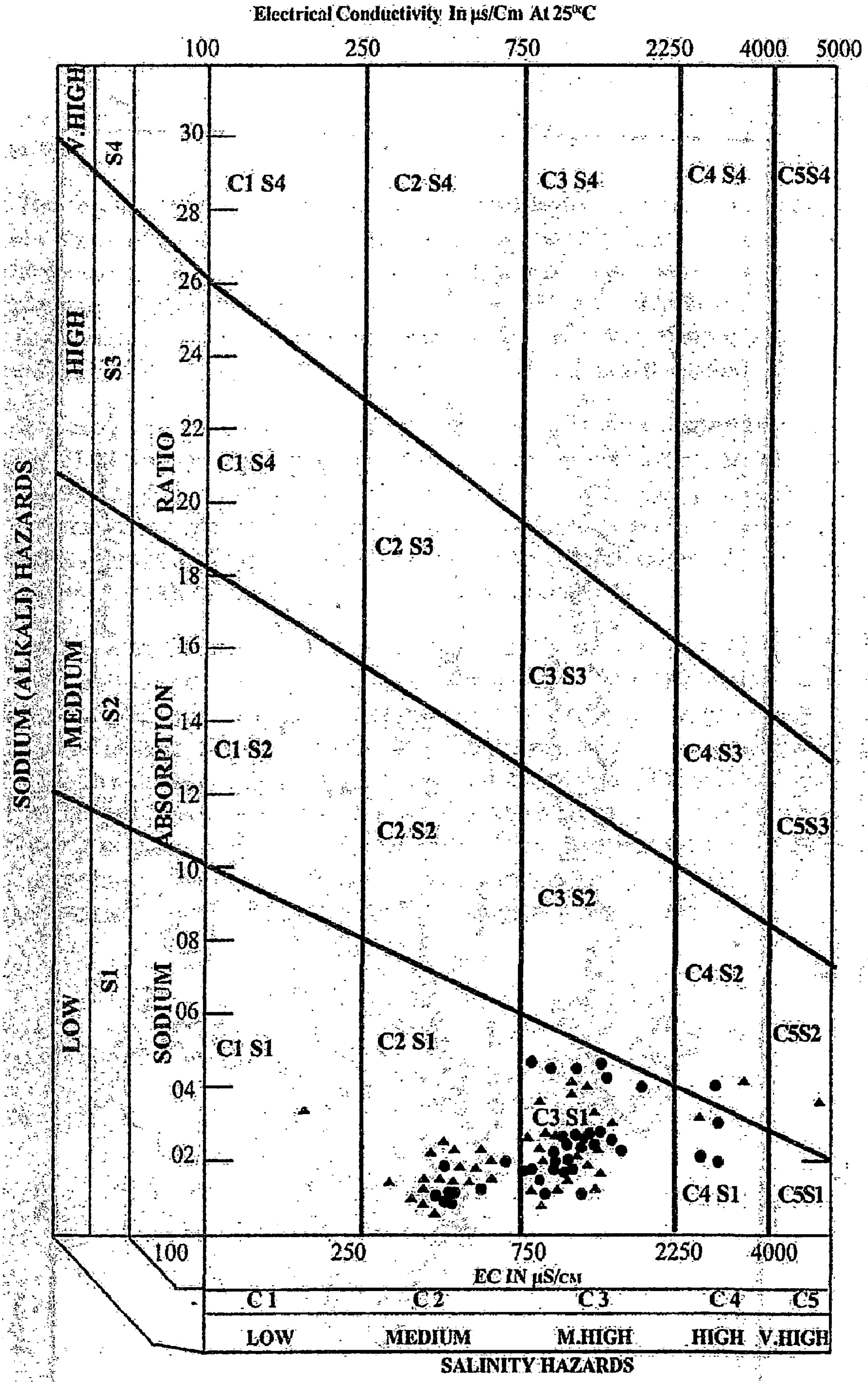


Fig 4.2

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : RAEBARELI

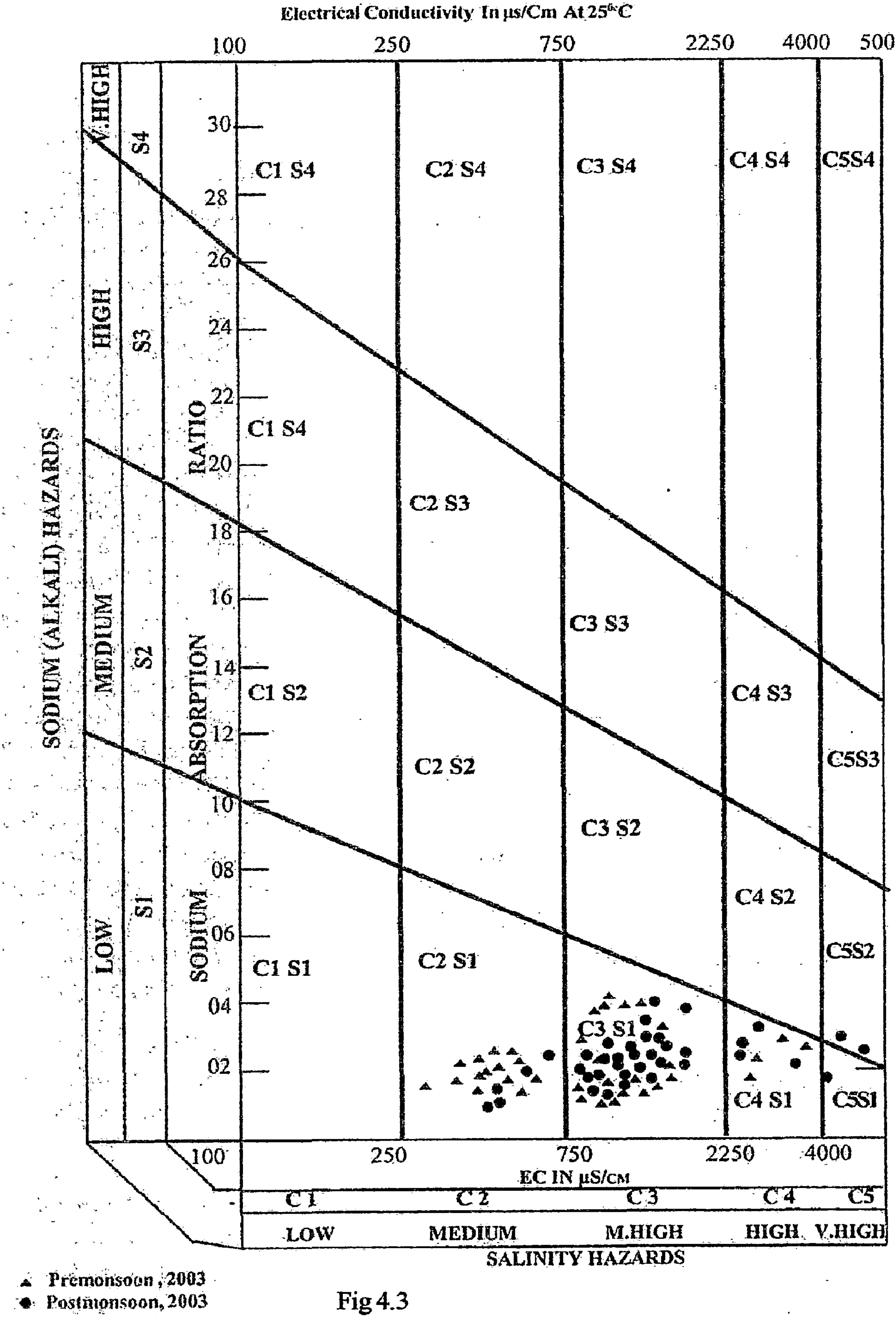
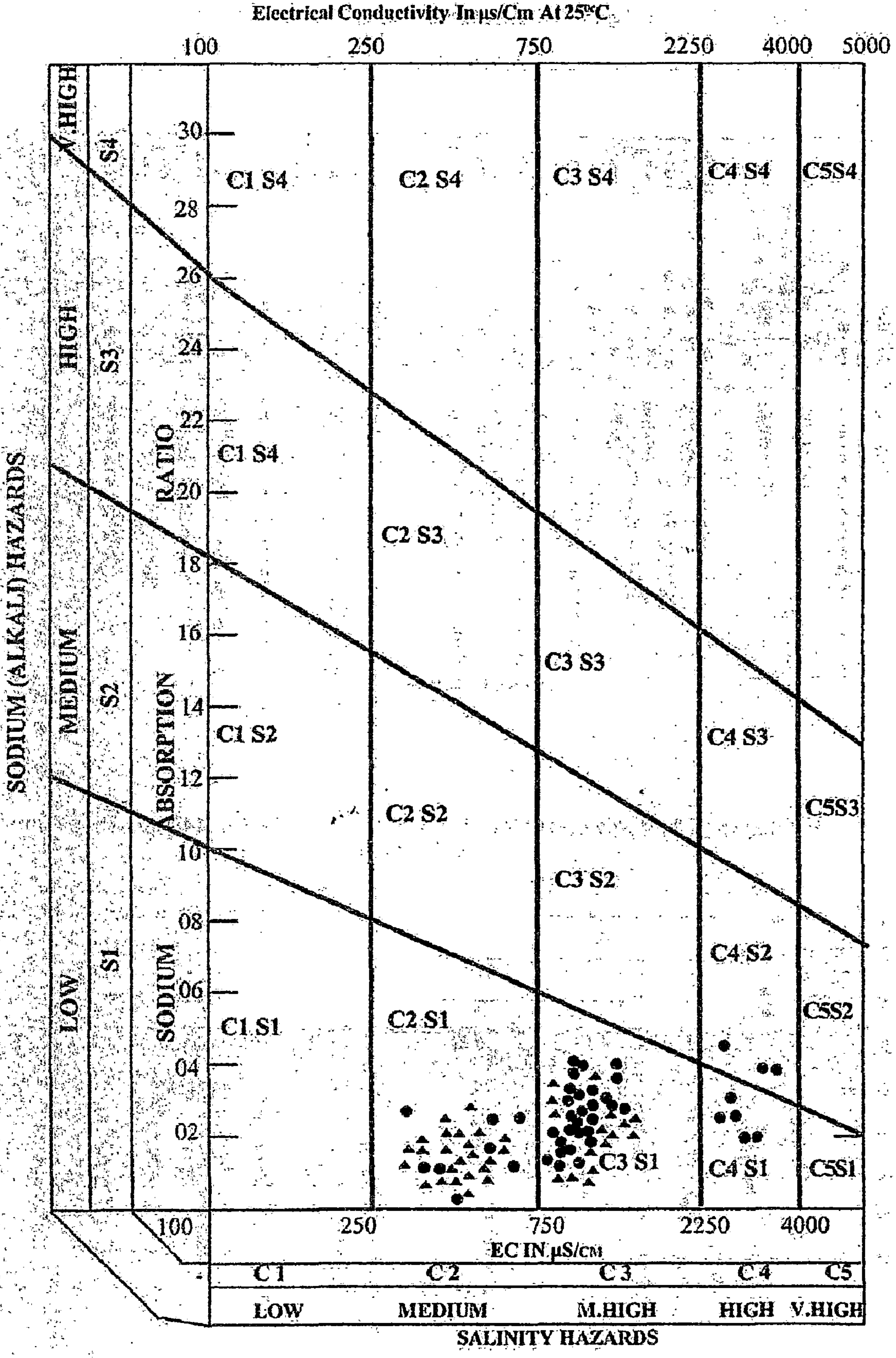


Fig 4.3

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : SULTANPUR



MONSOON-2003

Fig 4.4

▲ Premonsoon ,2003
● Postmonsoon, 2003

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : AZAMGARH

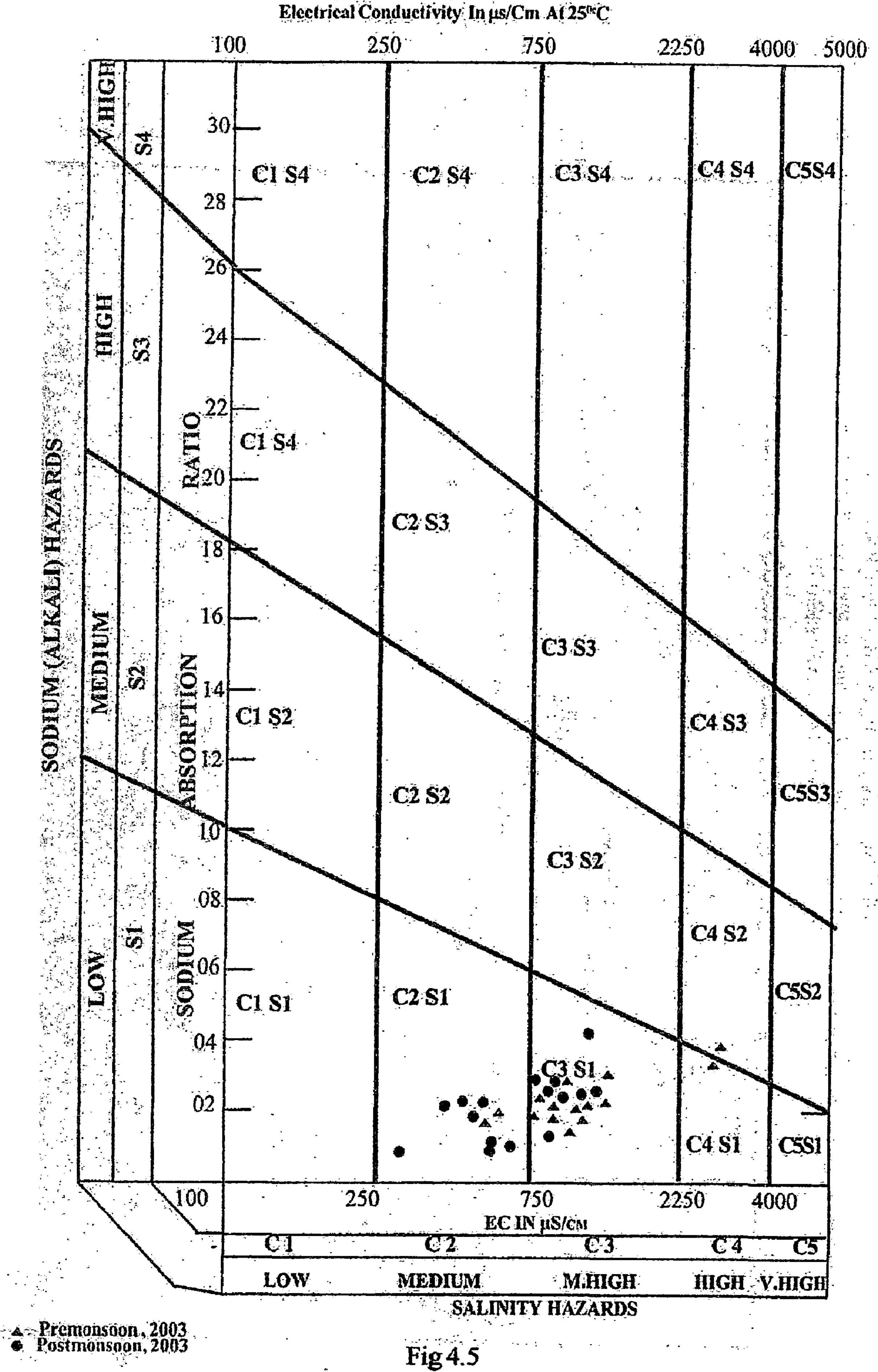


Fig 4.5

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : BULANDSHAHAR

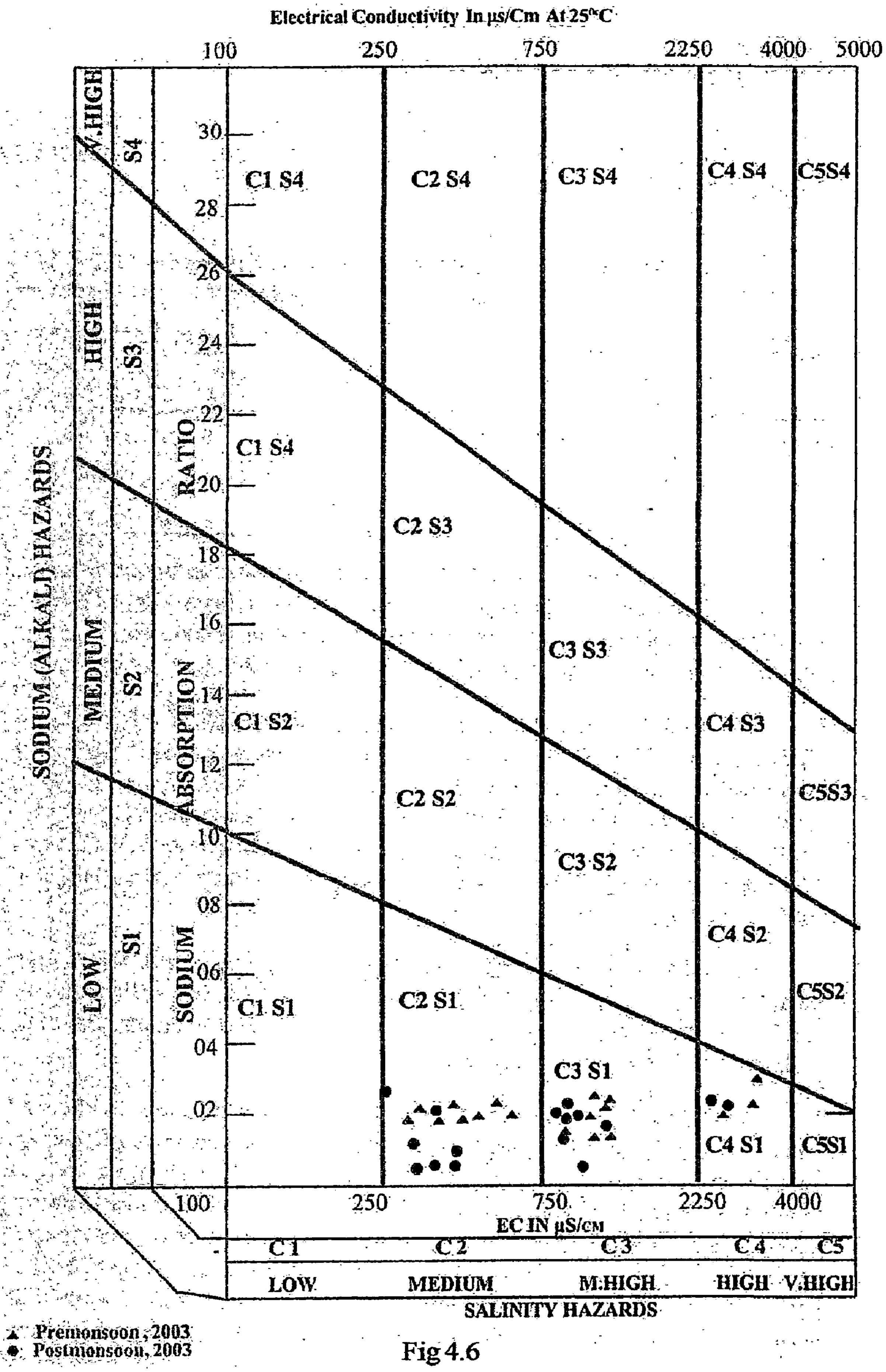
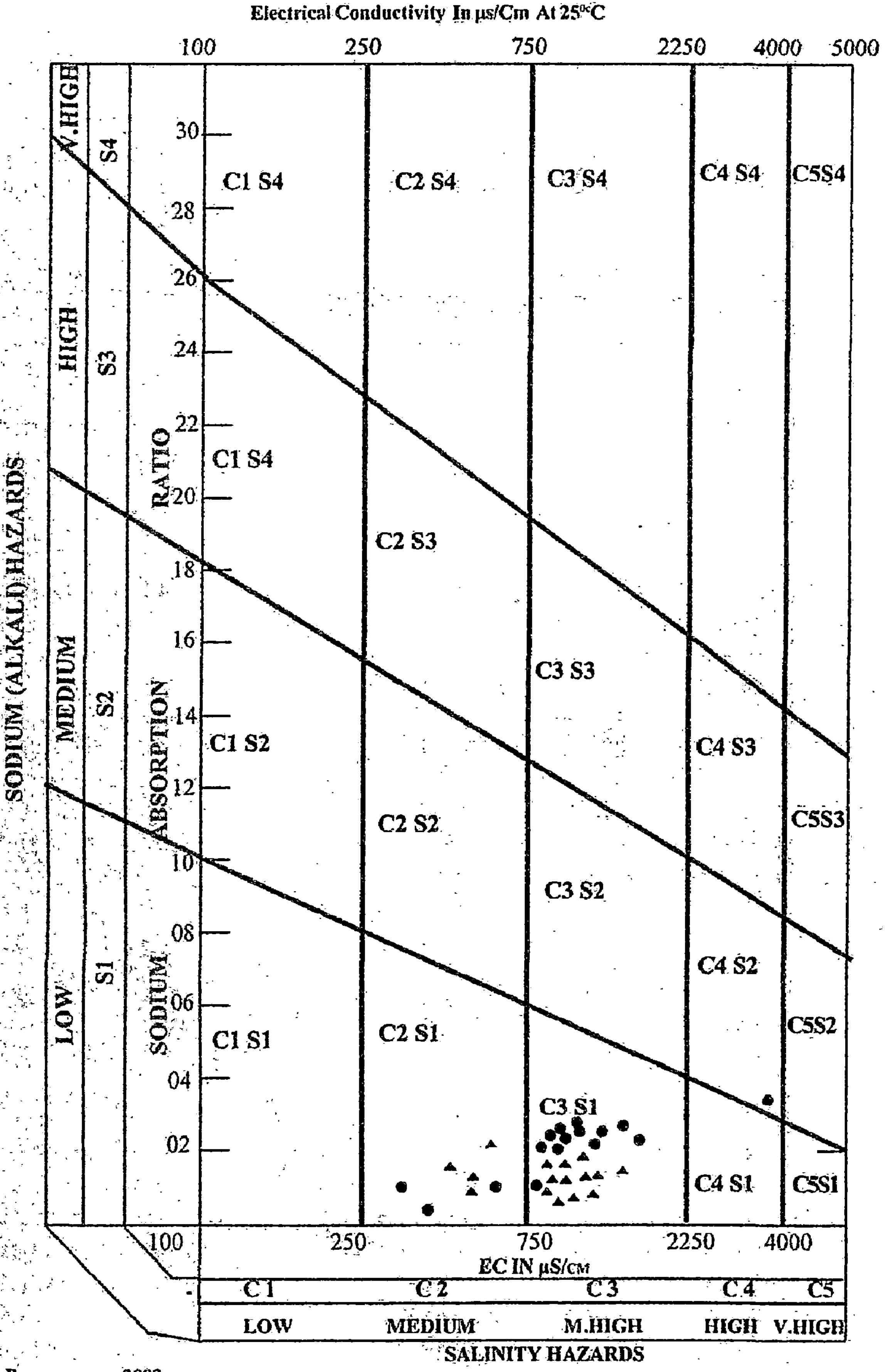


Fig 4.6

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : JAUNPUR



▲ Premonsoon, 2003
● Postmonsoon, 2003

Fig 4.7

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District :KANPUR

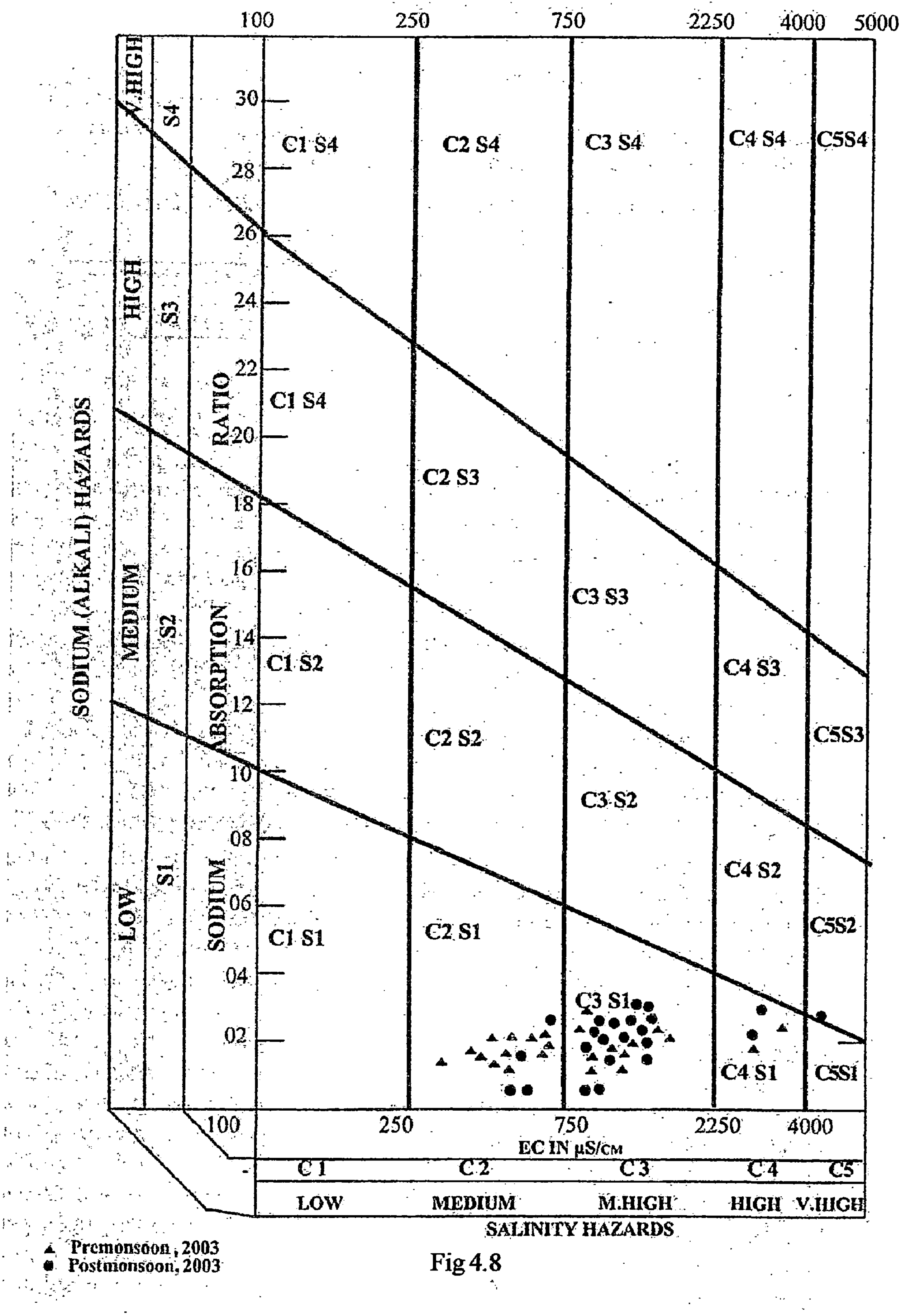


Fig 4.8

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : UNNAO

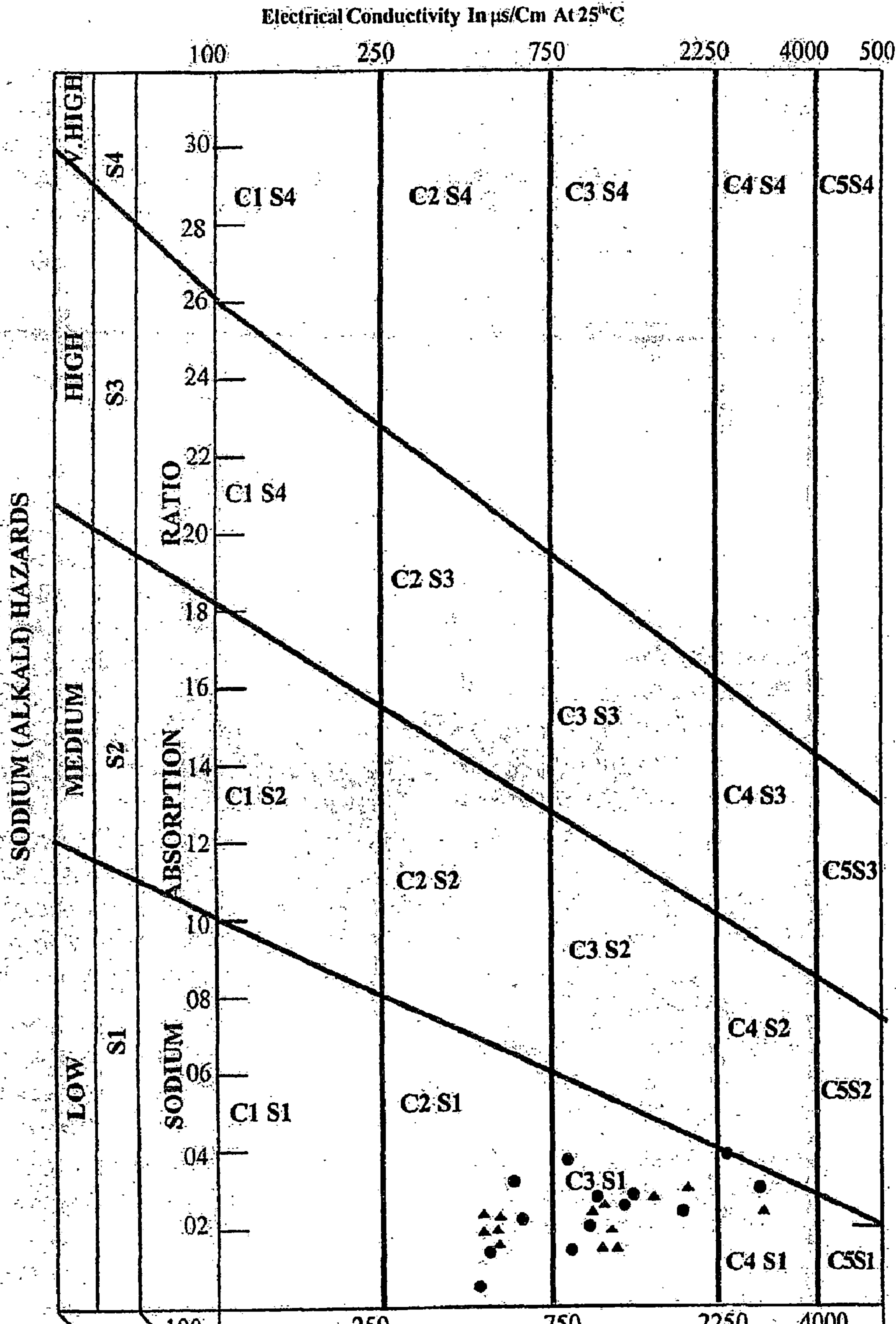


Fig 4.9

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM
District : HATHRAS

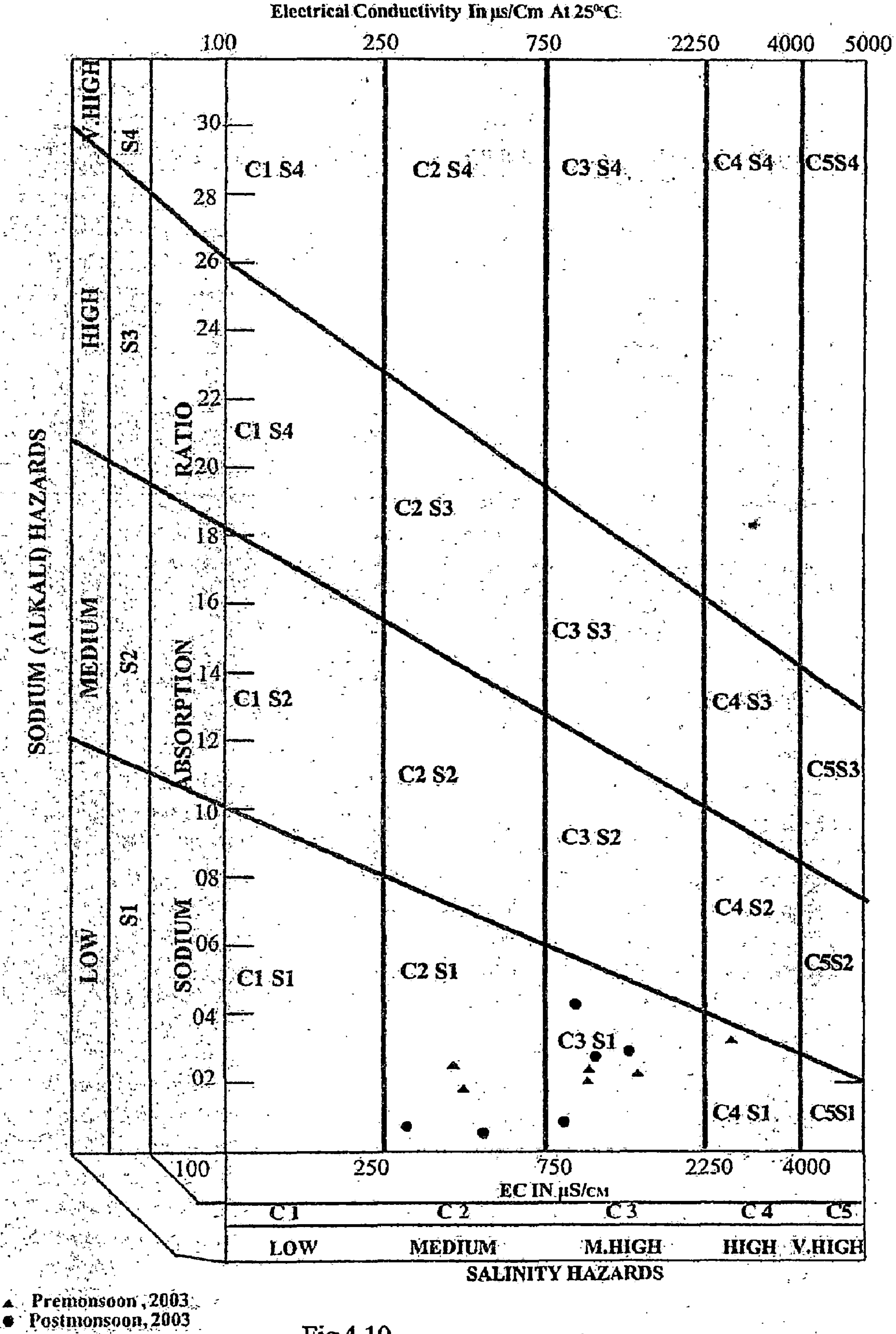


Fig 4.10

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : ALLAHABAD

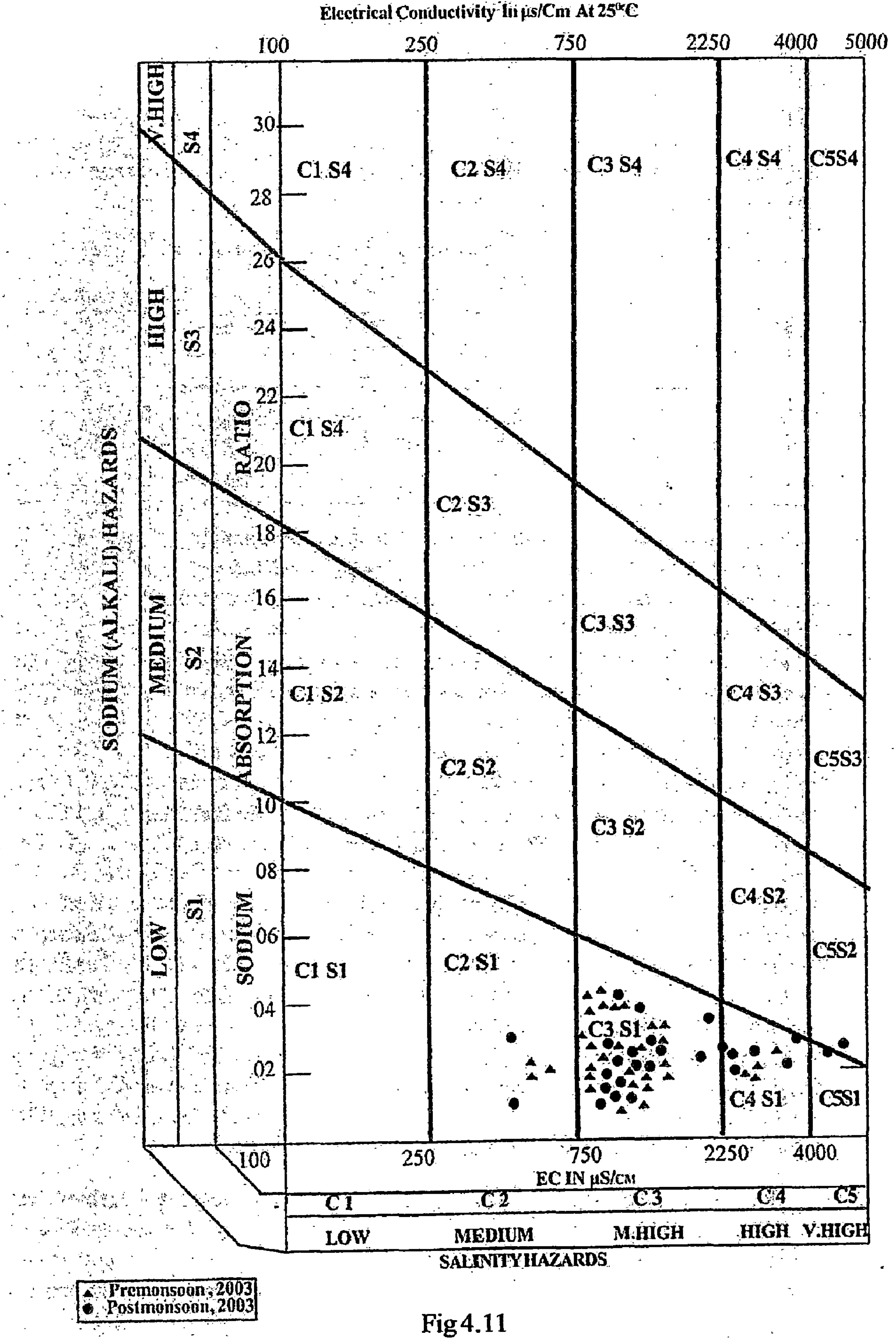
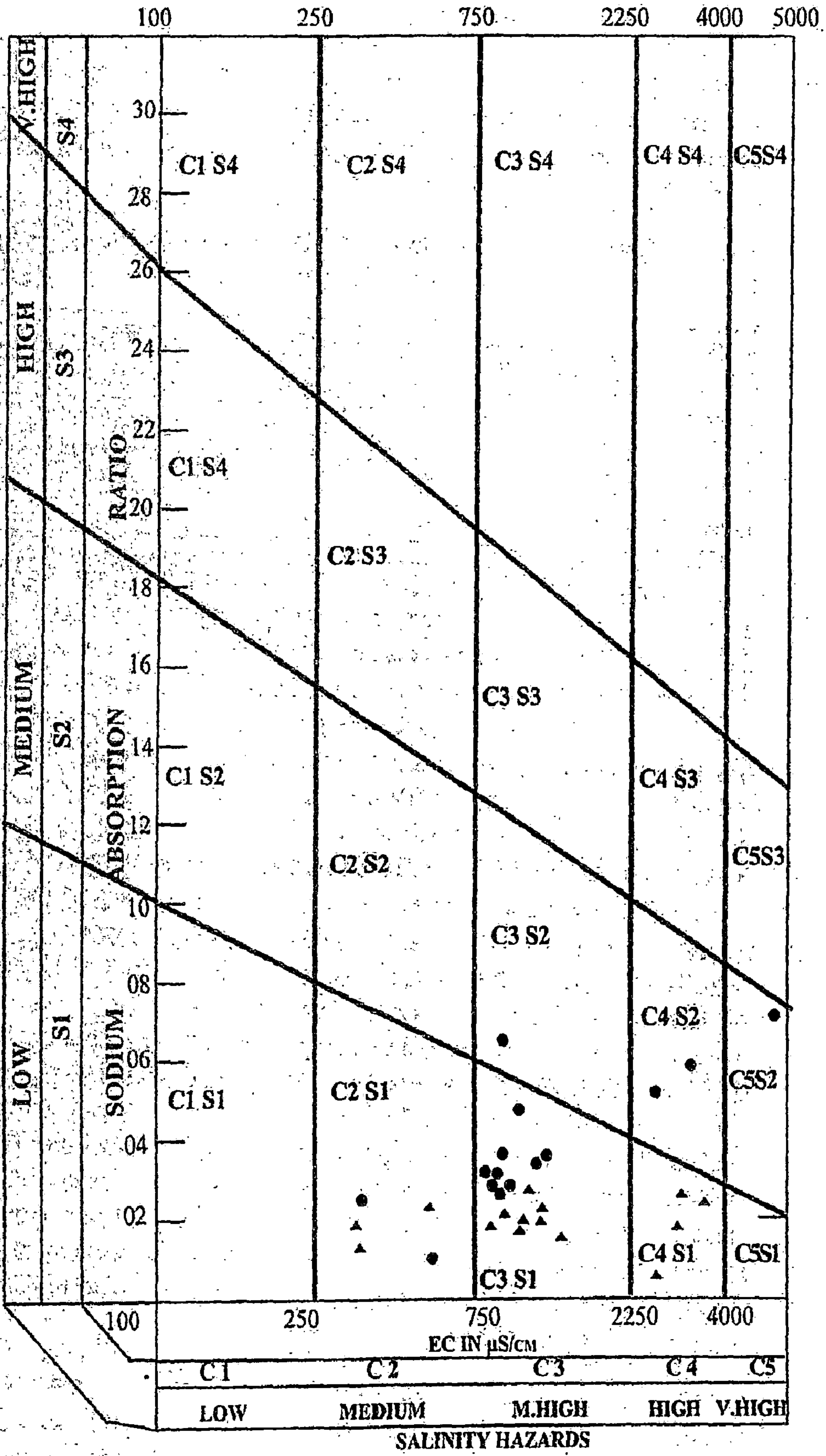


Fig 4.11

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : AURAIYA



▲ Premonsoon, 2003
● Postmonsoon, 2003

Fig 4.12

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : ETAH

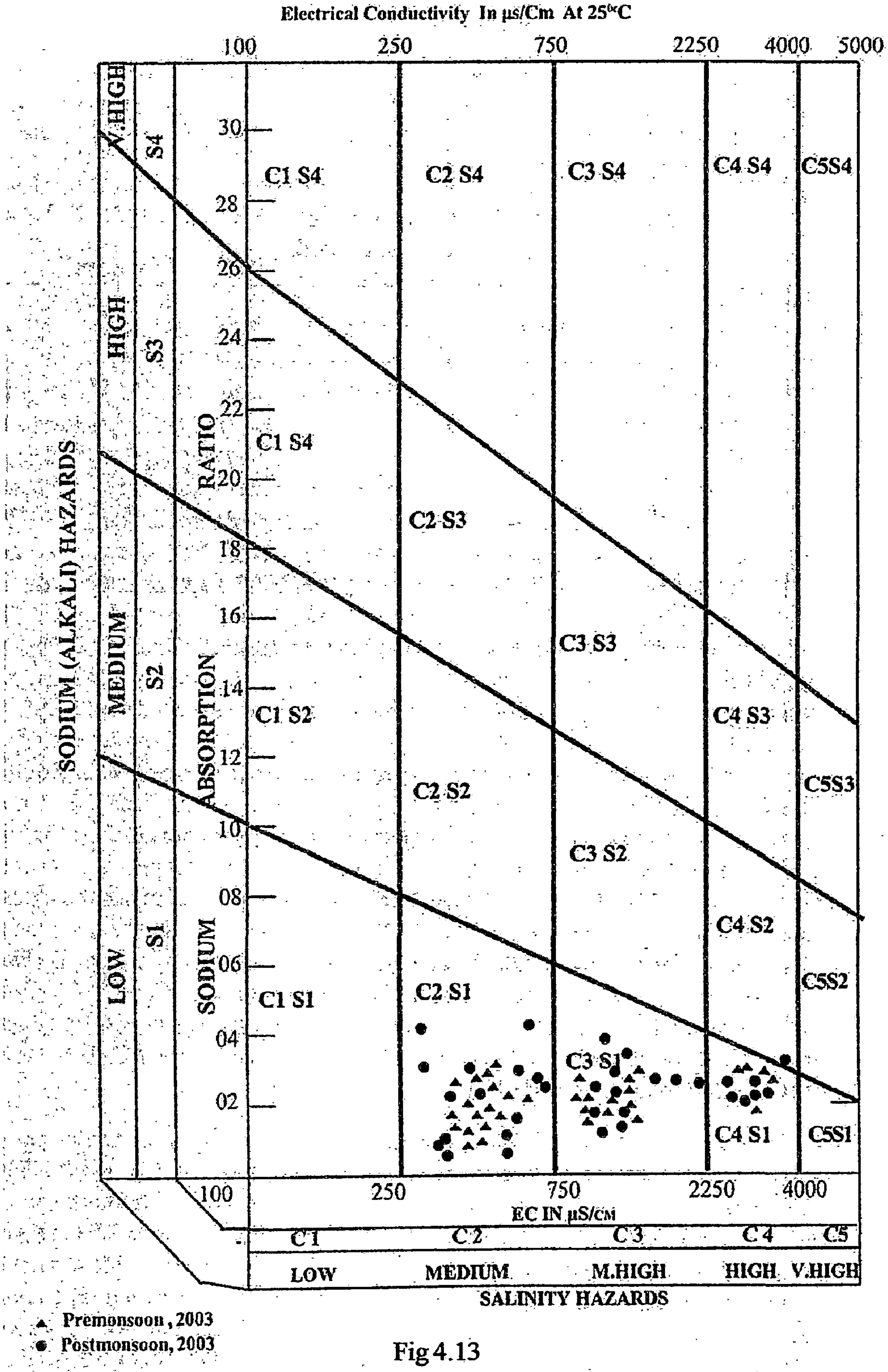
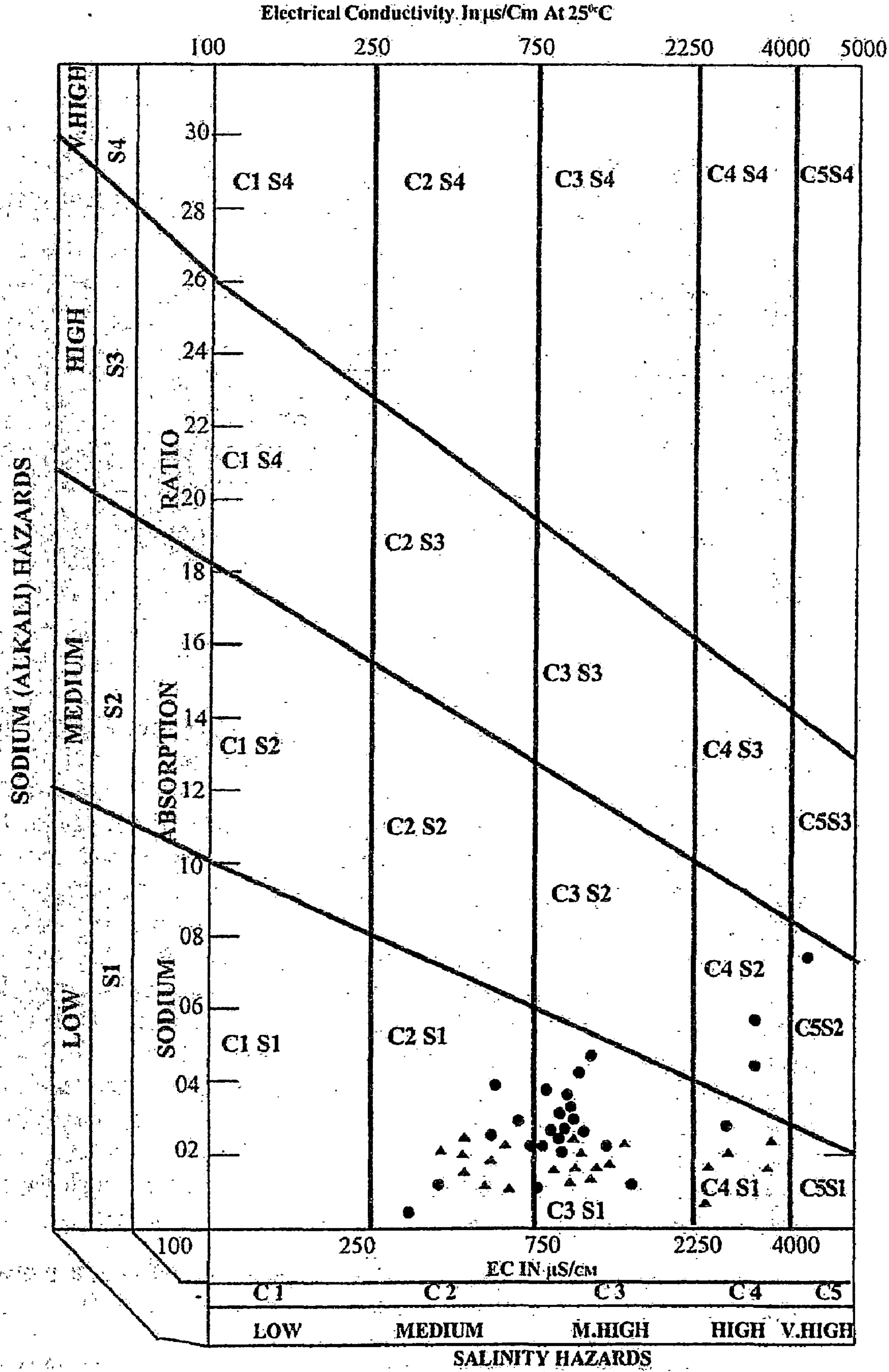


Fig 4.13

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : ETAWAH



▲ Premonsoon, 2003
● Postmonsoon, 2003

Fig 4.14

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : FATEHPUR

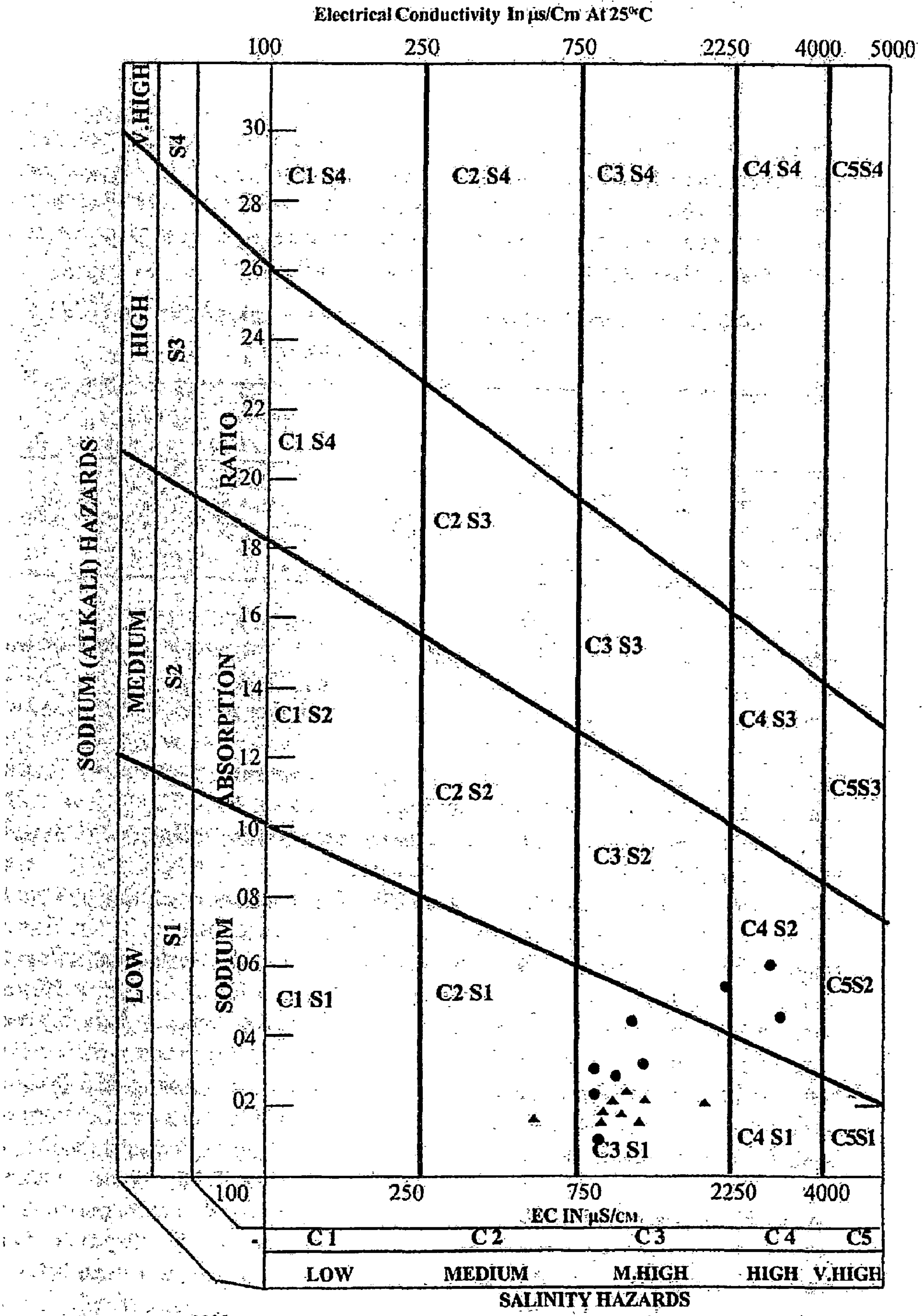
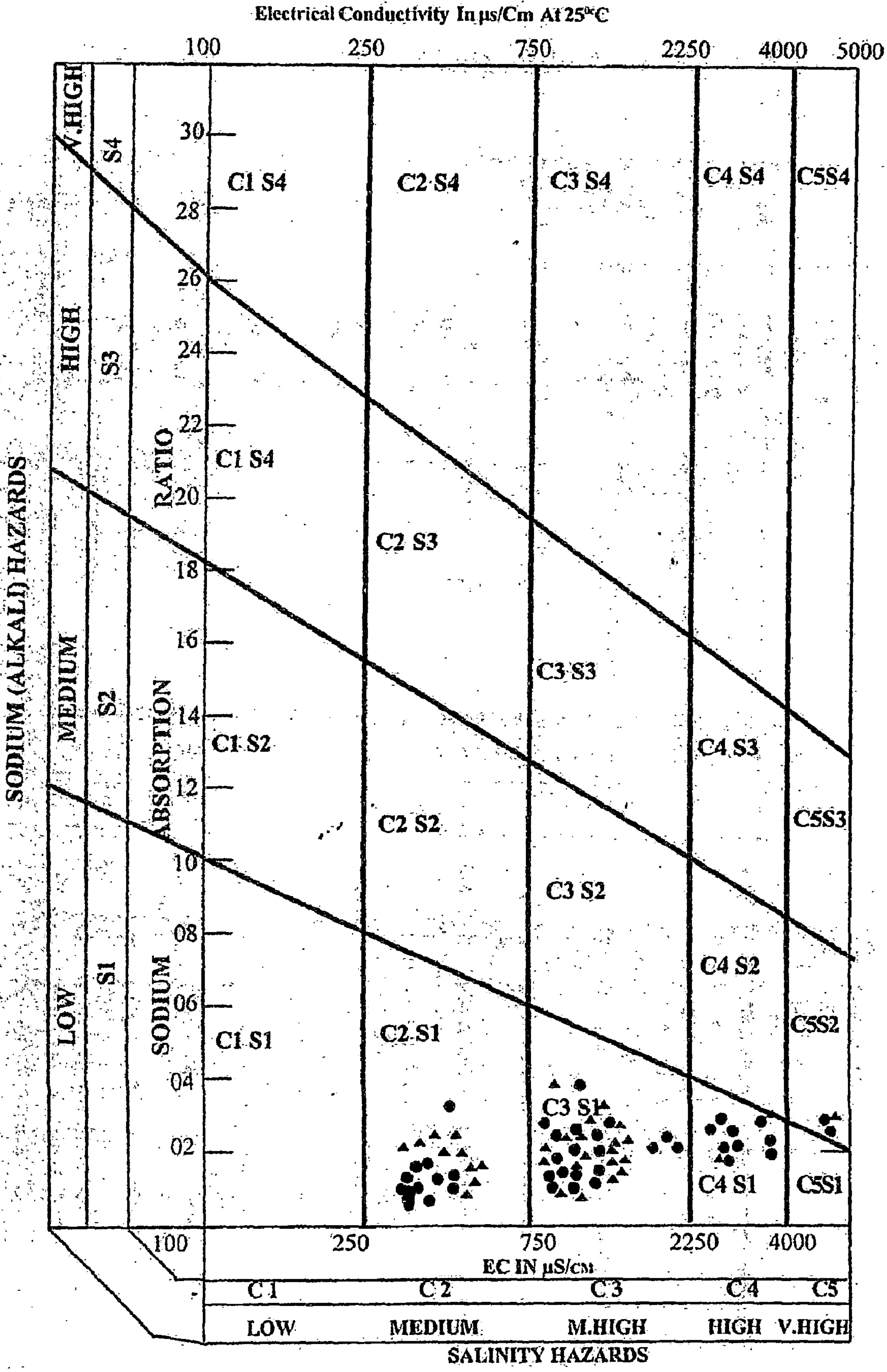


Fig 4.15

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : HARDOI



▲ Premonsoon, 2003
● Postmonsoon, 2003

Fig 4.16

CLASSIFICATION OF THE GROUNDWATER BASED ON ELECTRICAL CONDUCTIVITY AND SODIUM ADSORPTION RATIO: SALINITY DIAGRAM

District : MAINPURI

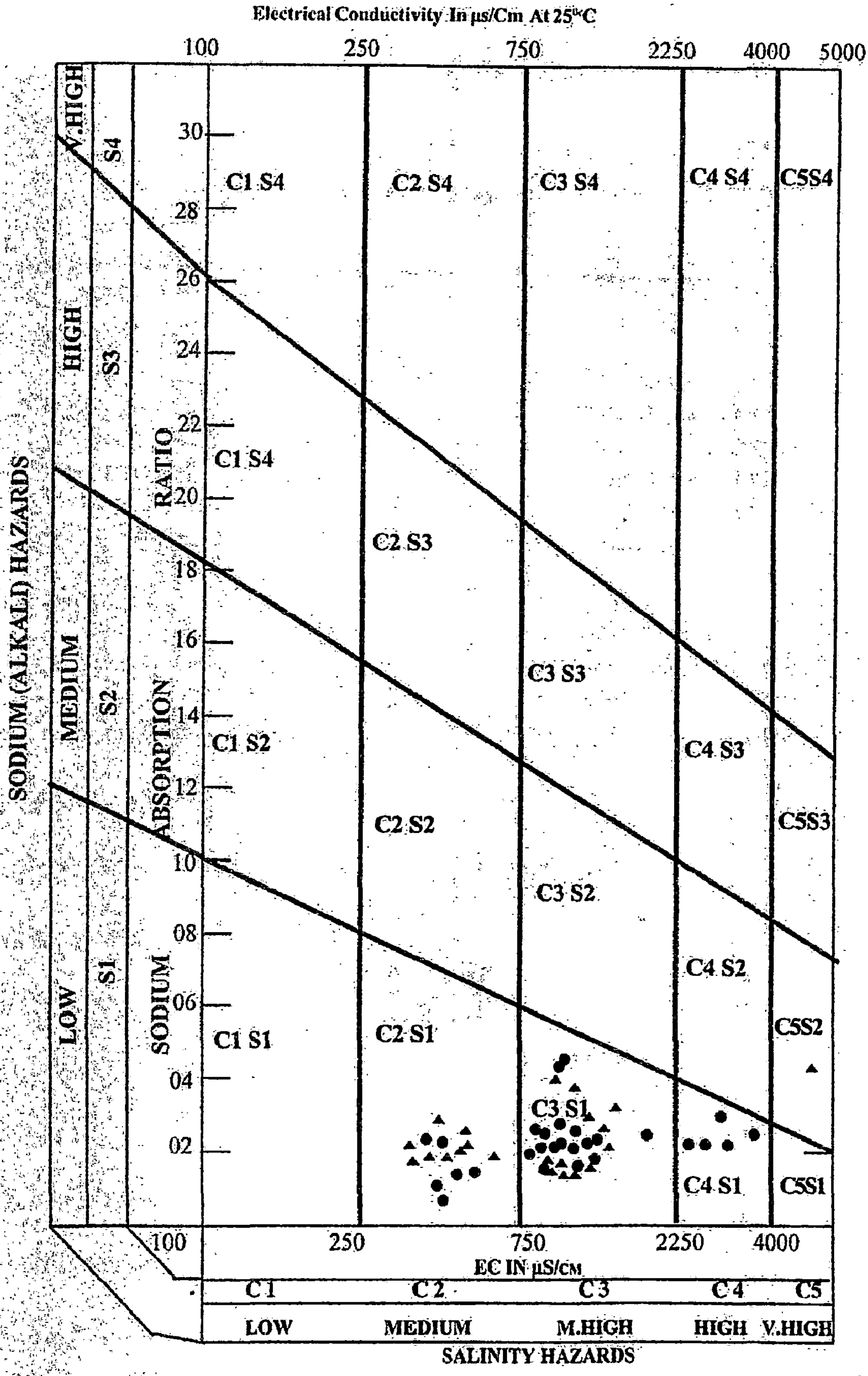


Fig 4.17

Table 4.1

DETAILED GROUND WATER MONITORING - PHASE-I

DATABASE OF CHEMICAL ANALYSIS

VARIATION IN CHEMICAL PARAMETERS DURING DIFFERENT PERIOD IN INDIVIDUAL PIEZOMETER

Reclamation Area : Village - Ramalwa, District - Hardoi

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : March, 1996										
H/PC/5	7.8	1470	0.55	3.02	0	0.69	1.06	5.21	5.07	1.82
H/PC/6	8.1	1040	0.55	2.47	0	0.81	1.00	6.52	6.85	1.23
H/PC/7	7.4	1040	0.55	2.75	0	1.37	1.19	4.35	3.04	0.74
H/PC/8	7.9	780	0.55	1.37	0	1.94	2.18	1.17	0.84	-2.20
H/PC/9	7.7	320	0.55	1.65	0	2.5	2.69	1.15	0.70	-2.99
Period : May-June, 1996										
H/PC/5	8.4	790	1.98	1.98	0.26	0.73	0.74	9.00	10.50	4.36
H/PC/6	8.4	420	0.99	3.46	0.43	0.73	0.99	3.61	3.89	1.30
H/PC/7	8.0	510	0.99	3.46	0.37	0.98	2.46	3.48	2.65	1.18
H/PC/8	8.3	320	0.99	3.46	0.25	0.73	1.97	0.78	0.67	-0.78
H/PC/9	8.4	310	0.99	2.47	0.42	0.49	1.72	0.65	0.60	0.50
Period : October-November, 1996										
H/PC/5	7.7	1000	0	12.74	0.34	2.34	1.04	3.91	2.31	4.36
H/PC/6	7.8	800	0	6.76	0.08	2.60	2.86	3.48	2.10	1.30
H/PC/7	7.7	1000	0	6.90	0.26	2.86	2.86	3.28	1.23	1.18
H/PC/8	8.2	700	0.52	5.98	1.11	2.86	6.18	0.82	0.42	-0.78
H/PC/9	8.3	800	0.52	10.92	0.26	2.86	3.48	0.96	0.61	6.50
Period : March, 1997										
H/PC/5	8.7	690	1.06	6.36	0	1.04	1.82	2.41	2.02	4.56
H/PC/6	8.5	610	0.53	6.09	0	2.86	2.08	1.22	0.78	1.68
H/PC/7	8.6	620	0.53	5.83	0	2.34	2.60	1.35	0.86	1.42
H/PC/8	8.6	390	0.53	3.97	0	1.30	2.08	1.00	0.77	1.12
H/PC/9	8.7	420	0.53	3.97	0	1.30	2.34	1.02	0.76	0.86
Period : May-June, 1997										
H/PC/5	7.9	660	0	7.42	0	2.60	1.56	1.69	1.17	3.26
H/PC/6	7.8	588	0	6.62	0	3.12	2.34	0.74	0.45	1.16
H/PC/7	7.9	660	0	3.36	0	2.60	1.82	0.69	0.46	-1.06
H/PC/8	8.1	546	0	5.87	0	2.86	3.38	0.48	0.27	-0.37
H/PC/9	7.9	558	0	6.33	0	2.60	2.60	0.56	0.35	-1.13

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : October-November, 1997										
H/PC/5	7.8	860	0	8.46	0	2.77	3.60	1.13	0.63	2.09
H/PC/6	8.1	780	0	8.22	0	2.47	3.38	1.22	0.71	2.37
H/PC/7	7.8	640	0	6.81	0	2.70	2.92	0.39	0.23	1.19
H/PC/8	8.1	676	0	6.81	0	2.25	2.92	1.35	0.34	1.64
H/PC/9	7.9	800	0	7.75	0	2.47	3.83	1.17	0.66	1.45
Period : March, 1998										
H/PC/5	7.8	656	0	6.00	0	2.91	1.71	1.17	0.70	1.38
H/PC/6	7.9	595	0	5.34	0	2.97	2.14	0.65	0.40	0.23
H/PC/7	7.5	581	0	5.80	0	2.91	2.48	0.69	0.40	0.41
H/PC/8	8.0	556	0	5.28	0	3.02	1.82	0.56	0.30	0.44
H/PC/9	8.1	552	0	6.83	0	2.53	4.23	0.61	0.33	0.07
Period : May-June, 1998										
H/PC/5	8.5	633	0.9	3.60	0.51	0.38	3.85	0.86	0.09	1.69
H/PC/6	8.4	581	0.45	3.15	0.68	0.71	3.30	0.47	0.03	1.24
H/PC/7	8.6	465	0.9	2.70	0.64	0.60	3.36	0.43	0.30	1.01
H/PC/8	8.4	467	0.45	2.92	0.66	0.55	1.92	1.28	1.15	1.06
H/PC/9	8.6	486	0.45	2.70	0.86	0.66	1.87	1.32	1.17	1.01
Period : October-November, 1998										
H/PC/5	7.6	702	0	6.75	0	2.48	2.59	1.17	0.73	1.69
H/PC/6	7.5	648	0	6.30	0	2.58	2.48	0.91	0.57	1.24
H/PC/7	8.4	621	0.45	5.40	0	2.36	2.48	0.87	0.56	1.01
H/PC/8	8.5	575	0.45	4.95	0	1.87	2.47	0.91	0.62	1.06
H/PC/9	8.4	612	0.45	5.40	0	0.55	4.29	1.17	0.75	1.01
Period : Post Rabi, 1999										
H/PC/5	7.8	820	0	6.65	0.38	5.50	2.03	0.91	0.47	-0.88
H/PC/6	7.8	876	0	6.65	0.12	6.27	1.02	0.76	0.40	-0.64
H/PC/7	7.9	864	0	6.30	0.41	5.83	2.57	0.72	0.35	-2.10
H/PC/8	7.8	1050	0	8.22	0.09	6.05	3.08	0.67	0.31	-0.91
H/PC/9	8.4	528	0.33	4.62	0.16	1.65	2.40	1.13	0.79	0.90
Period : May-June, 1999										
H/PC/5	8.5	640	0.66	4.95	0	1.80	2.70	1.48	0.94	2.44
H/PC/6	8.4	654	0.66	5.11	0	2.10	2.55	1.41	0.42	0.97
H/PC/7	8.4	672	0.66	5.11	0	1.65	1.50	3.02	2.41	2.28
H/PC/8	8.5	460	0.66	3.46	0	1.20	2.25	0.91	0.69	0.48
H/PC/9	7.7	1000	0	7.27	0	5.83	4.07	0.96	0.43	1.08
Period : October-November, 1999										
H/PC/5	7.5	653	0	6.76	0.04	2.02	2.30	1.62	1.10	2.44
H/PC/6	7.5	605	0	6.27	0.04	1.48	3.82	1.14	0.70	0.97
H/PC/7	7.5	508	0	5.11	0.06	2.29	0.54	1.94	1.63	2.28
H/PC/8	7.5	567	0	5.61	0.06	2.70	2.43	1.01	0.63	0.48
H/PC/9	7.6	562	0	5.94	0.08	2.97	1.89	1.05	0.67	1.08

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : March, 2000										
H/PC/5	8.4	690	0.53	5.35	0.82	2.69	3.29	1.05	0.61	-0.10
H/PC/6	7.6	682	0	6.37	0.17	2.69	3.21	0.87	0.51	0.47
H/PC/7	8.5	577	0.53	4.59	0.16	1.95	2.30	1.47	1.01	0.87
H/PC/8	7.8	578	0	4.84	0.42	2.39	2.86	0.82	0.51	-0.41
H/PC/9	7.8	672	0	5.35	0.57	2.34	2.94	0.91	0.56	0.07
Period : May-June, 2000										
H/PC/5	8.2	689	0	5.80	0.07	1.99	3.18	1.39	0.86	0.63
H/PC/6	8.3	593	0.43	4.73	0.40	3.94	1.34	0.91	0.56	-0.12
H/PC/7	8.5	641	0.86	5.16	0.17	0.75	2.63	2.09	1.60	2.11
H/PC/8	8.2	498	0	4.30	0.12	1.24	2.71	1.00	0.71	0.35
H/PC/9	8.2	536	0	3.22	0.96	1.25	2.80	0.95	0.67	-0.83
Period : October-November, 2000										
H/PC/5	7.4	573	0	4.84	3.82	1.22	2.94	1.52	1.10	0.70
H/PC/6	7.4	547	0	4.08	1.05	1.36	2.37	1.30	1.00	0.35
H/PC/7	7.5	587	0	5.35	0.01	2.24	2.17	1.26	0.80	0.94
H/PC/8	7.6	505	0	4.33	0.81	1.32	2.75	1.02	0.70	0.26
H/PC/9	7.6	516	0	4.33	0.32	1.47	2.69	1.39	1.00	0.13
Period : May-June, 2001										
H/PC/5	8.9	404	0.93	2.55	0.20	1.02	1.14	1.39	1.34	1.31
H/PC/6	8.9	414	0.46	2.78	0.26	2.30	0.52	1.26	1.06	0.42
H/PC/7	8.0	467	-	3.70	0.62	2.55	0.89	0.88	0.67	0.26
H/PC/8	8.8	411	0.46	2.55	0.39	1.06	1.70	1.09	0.93	0.25
H/PC/9	8.9	426	0.46	2.78	0.16	1.10	1.59	1.30	1.12	0.55
Period : October-November, 2001										
H/PC/5	8.4	467	0.93	3.24	0.13	1.30	1.87	1.09	0.86	1.00
H/PC/6	8.5	433	0.46	3.47	0.10	2.40	1.46	0.91	0.66	0.08
H/PC/7	8.2	526	0	3.94	0.21	1.70	1.88	0.96	0.72	0.36
H/PC/8	8.5	412	0.46	3.24	0.17	1.75	2.05	0.83	0.60	-0.09
H/PC/9	8.4	463	0.46	3.7	0.19	1.70	1.96	0.96	0.71	0.51
Period : May-June, 2002										
H/PC/5	7.2	538	0	3.80	0.50	1.70	2.70	1.80	1.21	0.23
H/PC/6	7.3	684	0	4.60	0.50	2.10	2.30	1.80	1.21	-0.01
H/PC/7	7.1	522	0	4.50	0.10	1.90	2.40	1.50	1.02	0.62
H/PC/8	7.4	483	0	3.30	0.60	1.10	3.20	2.10	1.43	0.33
H/PC/9	7.3	490	0	4.30	0	0.80	4.50	2.00	1.23	1.56
Period : October-November, 2002										
H/PC/5	8.4	455	0.51	4.04	0.15	1.32	1.56	1.44	1.66	1.20
H/PC/6	8.2	430	0	4.29	0.15	1.57	1.42	1.23	1.36	1.02
H/PC/7	8.2	453	0	3.79	0.15	1.28	1.46	1.12	1.05	0.96
H/PC/8	8.3	413	0	3.79	0.15	1.13	1.56	1.38	1.10	1.19
H/PC/9	8.3	429	0	4.04	0.15	1.23	1.86	1.18	0.95	0.95

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : Post Rabi, 2003										
H/PC/5	7.6	503	0	4.20	0.43	1.35	2.02	1.47	0.80	0.40
H/PC/6	7.5	506	0	4.40	0.23	1.72	7.95	1.28	0.73	0.33
H/PC/7	7.4	505	0	4.20	0.37	1.64	2.35	1.09	0.18	0.27
H/PC/8	7.7	460	0	3.70	0.41	1.44	2.05	1.02	0.21	0.27
H/PC/9	7.7	467	0	3.90	0.39	1.34	2.17	1.18	0.43	0.31
Period : May-June, 2003										
H/PC/5	7.5	451	0	3.63	0.42	2.05	1.23	1.65	0.35	1.29
H/PC/6	7.6	446	0	3.63	0.73	0.98	1.75	1.56	0.90	1.34
H/PC/7	7.6	494	0	3.63	0.63	1.97	1.65	1.43	0.01	1.06
H/PC/8	7.8	427	0	2.99	0.56	0.85	1.77	1.35	0.37	1.18
H/PC/9	8.0	463	0	3.63	1.06	1.83	1.54	1.56	0.26	1.20
Period : October-November, 2003										
H/PC/5	8.9	490	0	4.70	0.20	2.30	2.00	1.00	0.69	0.41
H/PC/6	8.5	480	0	4.30	0.20	2.30	1.70	1.00	0.69	0.25
H/PC/7	8.5	498	0	4.30	0.20	1.40	1.10	3.00	2.68	1.76
H/PC/8	8.5	464	0	2.80	0.20	2.20	1.60	1.00	0.69	-1.04
H/PC/9	8.6	459	0	3.00	0	2.00	1.50	1.20	0.81	-0.43

Reclamation Area : Village - Baikhara, District - Raebareli

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : May-June, 1996										
R/PC/5	7.7	700	0.99	6.93	0.32	3.19	2.71	2.17	1.84	1.50
R/PC/6	8.2	460	0.99	2.97	0.47	0.49	1.97	2.60	3.22	1.50
R/PC/7	7.6	770	0	7.42	0.20	3.44	2.46	2.69	1.64	1.42
R/PC/8	7.8	890	0.99	6.43	0.72	2.70	3.69	3.13	2.02	1.30
R/PC/9	7.8	870	0.99	10.89	0.98	2.70	2.71	4.04	1.46	1.30
Period : August-September, 1996										
R/PC/5	8.5	850	1.50	8.25	0	0.75	3.50	2.17	1.49	5.50
R/PC/6	8.6	860	1.50	9.00	0	0.75	1.50	4.34	4.09	8.25
R/PC/7	8.4	840	2.00	6.50	0	1.00	3.25	0.83	0.60	4.25
R/PC/8	8.6	860	2.00	7.75	0	1.25	2.25	3.21	2.37	6.25
R/PC/9	8.6	860	1.00	7.75	0	1.25	4.25	2.78	1.68	3.25
Period : October-November, 1996										
R/PC/5	8.4	1200	1.04	5.20	0.61	0.78	3.90	2.82	1.84	1.56
R/PC/6	8.2	1100	1.56	5.72	6.68	1.04	2.60	4.35	3.22	3.64
R/PC/7	8.3	900	1.04	4.42	0.34	1.04	2.86	2.30	1.64	1.56
R/PC/8	8.4	800	0.52	4.68	1.11	1.56	2.34	2.83	2.02	1.30
R/PC/9	8.2	1000	1.04	5.46	6.94	1.56	3.64	2.35	1.46	1.30

Sample No.	pH	EC µS/cm	CO$_3$ meq/L	HCO$_3$ meq/L	SO$_4$ meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : March, 1997										
R/PC/5	8.8	712	0.53	6.89	0.20	1.56	4.16	1.52	0.89	1.70
R/PC/6	8.8	743	0.53	7.15	0.20	1.56	2.86	2.24	1.51	3.26
R/PC/7	8.9	504	0.53	5.3	0.20	1.04	3.12	1.19	0.82	1.67
R/PC/8	8.8	530	0.53	5.56	0.20	1.56	3.38	1.19	0.75	4.96
R/PC/9	8.8	527	0.53	5.56	0.20	1.04	3.90	1.15	0.73	1.15
Period : May-June, 1997										
R/PC/5	8.9	708	0.49	6.80	0.63	0.84	4.20	1.39	0.80	2.25
R/PC/6	8.7	730	0.49	6.32	0.13	1.96	3.36	1.35	0.82	1.49
R/PC/7	8.5	757	0.97	5.34	0.18	3.08	3.64	1.00	0.54	-0.41
R/PC/8	8.5	718	0.49	6.80	0.13	3.08	3.92	1.00	0.53	0.29
R/PC/9	8.5	1120	0.49	10.69	0.16	2.52	3.08	4.00	1.67	5.58
Period : August-September, 1997										
R/PC/5	7.3	856	0	8.5	0	3.08	3.95	1.39	0.74	1.47
R/PC/6	8.3	829	0.49	7.78	0	2.80	6.32	1.39	0.65	-0.85
R/PC/7	8	725	0	6.32	0	2.52	3.36	0.30	0.17	0.44
R/PC/8	8.4	711	0.49	6.56	0	2.80	3.08	0.66	0.38	1.17
R/PC/9	8.4	738	0.49	6.8	0	3.08	3.10	1.08	0.61	1.11
Period : October-November, 1997										
R/PC/5	7.8	860	0	8.46	0	2.77	3.6	1.13	0.66	2.09
R/PC/6	8.1	780	0	8.22	0	2.47	3.38	1.22	0.71	2.37
R/PC/7	7.8	640	0	6.81	0	2.70	2.92	0.39	0.23	1.19
R/PC/8	8.1	676	0	6.81	0	2.25	2.92	1.35	0.08	1.64
R/PC/9	7.9	800	0	7.75	0	2.47	3.83	1.17	0.66	1.45
Period : March, 1998										
R/PC/5	8.1	683	0	6.21	0	2.58	3.58	1.13	0.64	0.05
R/PC/6	7.9	718	0	6.92	0	3.08	3.35	1.13	0.63	0.49
R/PC/7	7.9	648	0	6.06	0	3.08	2.80	0.87	0.54	0.18
R/PC/8	7.9	583	0	5.80	0	2.80	2.37	0.91	0.56	0.63
R/PC/9	7.5	727	0	6.47	0	2.58	4.18	0.91	0.49	-0.29
Period : May-June, 1998										
R/PC/5	8.4	511	0.90	2.47	1.2	0.71	3.03	1.00	1.43	1.92
R/PC/6	8.6	459	0.45	3.37	0.14	0.49	3.03	1.02	1.19	1.69
R/PC/7	8.4	497	0.90	3.60	0.02	0.77	2.75	0.78	0.77	2.60
R/PC/8	8.6	512	0.45	4.05	0.13	0.82	2.7	0.78	0.75	1.39
R/PC/9	8.8	589	1.35	3.82	0.17	0.71	3.47	0.78	0.67	1.13
Period : October-November, 1998										
R/PC/5	8.5	773	0.45	6.75	0	1.54	3.74	2.32	1.43	1.92
R/PC/6	8.4	738	0.45	6.3	0	1.70	3.36	1.89	1.19	1.69
R/PC/7	8.6	612	0.45	5.17	0	1.37	4.40	0.95	0.77	2.59
R/PC/8	8.4	560	0.45	4.95	0	1.15	2.86	1.06	0.75	1.39
R/PC/9	8.7	652	0.45	5.85	0	1.43	3.74	1.08	0.67	1.13

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : March, 1999										
R/PC/5	7.7	823	0	7.7	0.06	4.84	4.07	1.04	0.49	-1.21
/PC/6	7.8	794	0	7.87	0.17	5.50	1.02	1.39	0.77	1.35
/PC/7	8.0	768	0	6.47	0.49	5.61	2.57	0.78	0.39	-1.71
/PC/8	7.9	797	0.35	5.95	0.41	5.06	3.08	0.91	0.45	-1.84
/PC/9	8.1	971	0	7.87	0.14	5.61	4.07	0.79	0.35	-1.81
eriod : May-June, 1999										
/PC/5	8.4	932	0.16	8.58	0	2.20	4.70	1.78	0.76	1.06
/PC/6	8.6	958	0.99	7.92	0	1.60	4.10	3.29	0.89	0.59
/PC/7	8.4	792	0.66	6.60	0	0.90	4.50	2.13	0.77	0.35
/PC/8	8.5	832	0.99	6.60	0	0.96	4.86	2.00	0.66	-0.39
/PC/9	8.5	928	0.99	7.59	0	1.02	6.00	1.54	0.69	-0.36
eriod : October-November, 1999										
/PC/5	8.1	920	0	8.08	0.33	2.97	4.05	1.48	0.78	1.06
/PC/6	8.7	817	0.33	6.6	0.12	2.29	4.05	1.59	0.89	0.59
/PC/7	8.6	670	0.66	4.95	0.06	1.35	3.91	1.25	0.77	0.35
/PC/8	8.3	860	0.66	6.10	0.40	2.56	4.59	1.25	0.66	-0.39
/PC/9	8.6	720	0.66	4.78	0.14	1.21	4.59	1.19	0.69	-0.36
Period : March, 2000										
R/PC/5	7.7	845	0	6.88	0.76	3.04	4.61	1.26	0.64	-0.77
R/PC/6	7.7	761	0	6.37	0.48	2.09	4.08	1.43	0.81	0.20
R/PC/7	7.8	763	0	6.12	1.09	2.99	3.85	1.00	0.54	-0.72
R/PC/8	7.9	838	0	6.37	0.94	2.98	4.43	1.09	0.56	-1.04
R/PC/9	8.0	842	0	7.14	0.27	2.48	4.51	1.09	0.58	0.15
Period : May-June, 2000										
R/PC/5	7.6	822	0	7.74	0.14	2.49	5.28	1.56	0.79	-0.03
R/PC/6	7.7	763	0	7.09	0.10	2.44	3.38	1.69	0.99	1.27
R/PC/7	8.4	660	0.43	4.73	0.91	1.99	2.76	1.22	0.72	-0.59
R/PC/8	8.5	565	0.43	4.73	0.16	1.99	3.43	1.30	0.79	-0.26
R/PC/9	8.8	709	0.86	4.57	0.14	2.99	3.21	2.48	1.43	-0.77
Period : October-November, 2000										
R/PC/5	7.5	710	0	5.35	0.2	2.14	4.41	0.52	0.29	-1.20
R/PC/6	7.5	653	0	5.10	0.27	2.01	3.55	1.04	0.62	-0.46
R/PC/7	7.6	590	0	4.33	0.25	1.36	2.59	1.56	1.11	0.38
R/PC/8	7.5	667	0	4.84	0.24	1.49	2.79	2.09	1.43	0.56
R/PC/9	7.4	614	0	4.59	0.21	2.18	3.6	0.52	0.50	-1.19
Period : May-June, 2001										
R/PC/5	9.1	488	0.93	3.24	0.33	0.17	1.12	2.04	1.19	1.01
R/PC/6	9.0	472	0.46	3.47	0.33	0.19	1.32	1.26	1.64	1.36
R/PC/7	8.9	467	0.93	2.78	0.22	0.10	1.50	1.46	1.21	0.74
R/PC/8	8.9	400	1.39	3.01	0.33	0.12	2.73	4.11	0.82	-2.44
R/PC/9	8.95	433	0.46	3.47	0.33	0.17	1.08	1.90	1.06	0.96

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : October-November, 2001										
R/PC/5	7.9	847	0	7.64	0.21	2.79	3.57	1.43	0.80	1.28
R/PC/6	8.2	792	0	6.48	0.23	3.09	2.87	1.70	0.48	0.52
R/PC/7	8.2	577	0	4.86	0.21	1.24	1.95	1.87	1.48	1.67
R/PC/8	8.2	723	0	6.48	0.21	2.45	3.44	1.13	0.66	0.60
R/PC/9	8.2	784	0	6.95	0.23	3.24	3.24	0.96	0.83	0.46
Period : May-June, 2002										
R/PC/5	7.3	684	0	5.60	0.30	1.10	6.50	2.20	1.54	1.61
R/PC/6	7.5	620	0	5.60	0.30	1.70	3.70	2.30	1.69	2.00
R/PC/7	7.5	584	0	5.10	0.50	2.20	4.30	2.20	1.69	1.65
R/PC/8	7.5	578	0	5.10	0.30	1.70	4.00	2.40	1.80	1.57
R/PC/9	7.5	628	0	5.10	0.40	1.20	6.80	2.80	2.32	2.14
Period : October-November, 2002										
R/PC/5	7.9	456	0	4.60	0.19	1.01	2.08	1.98	1.59	1.51
R/PC/6	8.0	388	0	3.20	0.10	0.72	1.16	1.80	1.86	1.32
R/PC/7	-	-	Leaked	-	-	1.32	1.15	2.09	1.80	1.00
R/PC/8	8.3	460	0	4.10	0.13	1.25	1.66	1.78	1.48	1.419
R/PC/9	8.2	428	0	3.00	0.15	1.24	1.36	1.79	1.57	0.40
Period : Post-rabi, 2003										
R/PC/5	7.4	658	0	5.60	0.62	1.35	3.54	1.50	0.34	0.67
R/PC/6	7.4	602	0	5.30	0.11	1.79	2.44	1.67	0.41	1.09
R/PC/7	7.6	540	0	4.60	0.29	1.55	2.09	1.47	0.39	0.99
R/PC/8	7.6	548	0	4.40	0.56	1.69	2.18	1.37	0.35	0.53
R/PC/9	7.5	588	0	4.60	0.59	1.87	2.45	1.39	0.33	0.31
Period : May-June, 2003										
R/PC/5	7.4	501	0.85	1.50	2.04	1.44	2.11	1.39	1.04	-1.20
R/PC/6	7.9	566	0.43	3.21	1.69	1.09	2.58	2.30	1.70	-0.04
R/PC/7	7.9	472	0.43	2.56	1.15	1.86	1.94	1.43	1.04	-0.81
R/PC/8	7.7	522	0	4.06	0.90	1.07	2.04	1.78	1.43	0.95
R/PC/9	7.6	527	0	4.27	0.77	1.36	2.60	1.61	1.14	0.31
Period : October-November, 2003										
R/PC/5	7.8	739	0	7.30	0.10	2.80	3.10	2.00	1.16	1.41
R/PC/6	8.0	629	0	6.00	0	2.40	2.20	2.10	1.38	1.42
R/PC/7	8.0	567	0	5.60	0.10	2.40	2.10	1.10	0.71	1.02
R/PC/8	8.0	590	0	5.30	0.10	2.30	2.60	1.40	0.87	0.42
R/PC/9	7.9	584	0	5.30	0.10	2.60	2.00	1.10	0.73	0.70

Table 4.2

Detailed Ground Water Monitoring - Phase-II
Database of Chemical Analysis
Variation in Chemical Parameters during different period in individual piezometer

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : Post monsoon, 2000										
District : Mainpuri										
2M/PC/02	9.0	2770	2.55	15.30	3.07	5.47	18.87	4.65	1.35	-6.49
2M/PC/03	8.5	3670	4.59	18.87	1.73	4.44	28.44	4.35	1.07	-9.42
2M/PC/04	9.1	1630	1.02	8.16	1.44	4.45	8.68	4.04	1.58	-3.95
District : Pratapgarh										
2P/PC/01	9.0	746	0.15	5.35	0.41	1.45	3.63	1.83	1.15	0.42
2P/PC/02	9.1	938	1.53	6.37	0.29	1.60	3.21	2.83	1.82	3.09
2P/PC/03	9.1	767	2.04	4.59	0.32	1.10	3.05	2.65	1.84	2.48
2P/PC/04	9.0	698	1.53	4.08	0.48	1.45	3.29	1.97	1.28	0.87
District : Auraiya										
2T-I/PC/01	9.0	661	0.51	4.59	0.71	1.30	3.29	1.87	1.24	0.51
2T-I/PC/02	9.0	613	1.04	4.86	0.87	1.10	2.55	2.09	1.55	2.25
2T-I/PC/03	8.9	713	0.51	6.37	0.27	1.39	3.52	1.74	1.10	1.97
2T-II/PC/01	9.2	680	1.53	4.08	1.29	2.13	2.48	2.78	1.83	1.00
2T-II/PC/02	9.2	852	1.53	5.86	0.18	2.02	3.55	2.96	1.77	1.82
Period : Pre monsoon, 2001										
District : Mainpuri										
2M/PC/02	8.4	2962	0.69	8.80	1.14	7.35	6.92	10.84	4.06	-4.70
2M/PC/03	7.8	3142	0	10.90	5.08	5.10	10.32	12.32	4.44	-4.52
2M/PC/03					-------- Dry --------					
District : Pratapgarh										
2P/PC/01	8.8	2284	6.90	13.43	0.42	7.15	10.62	3.64	1.22	2.56
2P/PC/02	9.4	635	0.93	4.17	0.71	1.21	2.87	2.03	1.42	1.02
2P/PC/03	9.1	753	0.93	4.17	1.37	1.80	2.54	2.74	1.86	0.76
2P/PC/04	9.0	802	1.38	6.02	0.50	1.85	2.70	3.43	2.27	2.85
District : Auraiya										
2T-I/PC/01	8.4	610	0.93	4.40	0.17	1.23	1.46	3.22	2.78	2.64
2T-I/PC/02	8.3	1446	0.93	10.42	0.87	6.30	3.74	6.69	2.99	1.31
2T-II/PC/01	8.0	685	0	5.79	0.29	1.06	1.69	3.26	2.78	3.04
2T-II/PC/02	8.4	810	1.38	5.79	0.42	1.75	3.62	2.86	1.75	1.80

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : Post monsoon, 2001										
District : Mainpuri										
2M/PC/02	8.1	3320	0.46	8.80	6.46	4.10	8.20	12.40	5.00	-3.04
2M/PC/03	8.2	3210	-	21.76	6.46	7.63	12.00	11.70	3.73	2.13
2M/PC/04				-------- Dry ----------						
District : Pratapgarh										
2P/PC/01	8.3	798	-	6.71	0.42	1.46	3.54	2.48	1.57	1.71
2P/PC/02	8.6	4850	2.30	19.80	7.56	5.46	8.70	24.20	9.09	7.94
2P/PC/03	8.7	850	0.93	6.71	0.48	1.00	3.13	4.06	2.83	3.51
2P/PC/04				-------- Dry ----------						
District : Auraiya										
2T-I/PC/01	7.8	790	0	5.56	1.44	1.65	3.21	2.83	1.82	0.70
2T-I/PC/02	8.0	736	0	6.71	0.35	1.90	3.84	1.76	1.04	0.97
2T-I/PC/03	8.2	647	0	5.79	0.27	2.54	2.20	1.65	1.07	1.05
2T-II/PC/01	8.2	7.66	0	6.71	0.38	1.15	3.87	2.22	1.40	1.69
2T-II/PC/02	8.2	910	0	8.33	0.31	2.15	3.29	3.52	2.13	2.93
Period : Post Rabi (March, 2002)										
District : Mainpuri										
2M/PC/02	10.0	412	0.50	2.60	0.20	1.10	1.40	1.60	1.43	0.60
2M/PC/03	8.5	510	0.50	3.00	0.20	1.30	2.60	1.20	0.88	-0.40
2M/PC/04				-------- Dry ----------						
District : Pratapgarh										
2P/PC/01	9.0	799	0.90	4.80	0.20	1.40	3.90	2.60	1.60	0.40
2P/PC/02				-------- Damaged ----------						
2P/PC/03	8.8	516	0.50	2.60	0.30	1.30	2.20	1.40	1.09	-0.40
2P/PC/04				-------- Damaged ----------						
District : Auraiya										
2T-I/PC/01	9.06	1375	0.90	8.70	0.70	2.50	5.20	5.30	2.68	1.90
2T-I/PC/02	9.15	1372	0.90	8.10	0.40	2.70	5.90	4.90	2.35	0.40
2T-I/PC/03				-------- Dry ----------						
2T-II/PC/01	9.19	680	1.09	3.10	0.20	1.50	2.70	2.60	1.60	-0.01
2T-II/PC/02	9.24	689	0.90	3.30	0.30	1.40	2.90	2.40	1.62	-0.10

Sample No.	pH	EC µS/cm	CO_3 meq/L	HCO_3 meq/L	SO_4 meq/L	Ca meq/L	Mg meq/L	Na meq/L	SAR	RSC meq/L
Period : Pre monsoon, 2002										
District : Mainpuri										
2M/PC/02	8.6	3960	0.50	10.90	5.50	5.30	1.60	22.40	9.06	-0.79
2M/PC/03	7.9	4960	0	21.80	7.50	13.70	3.90	22.20	6.41	-2.17
2M/PC/04				-------- Dry ---------						
District : Pratapgarh										
2P/PC/01	8.8	619	1.00	6.10	0.40	0.80	11.40	2.90	1.62	2.05
2P/PC/02				-------- Damaged ----------						
2P/PC/03	8.9	628	1.00	4.30	0.70	1.20	3.80	3.20	2.24	1.72
2P/PC/04				-------- Damaged ----------						
District : Auriya										
2T-I/PC/01	8.6	595	1.00	3.80	0.40	1.30	2.90	2.20	1.69	1.40
2T-I/PC/02				-------- Dry ----------						
2T-I/PC/03				-------- Dry ----------						
2T-II/PC/01	8.3	644	0	4.30	0.90	1.70	5.60	2.60	1.97	0.68
2T-II/PC/02	8.7	681	1.00	4.30	0.50	1.30	3.20	2.60	1.79	1.21
Period : Post monsoon, 2002										
District : Mainpuri										
2M/PC/02	8.3	1290	0.51	7.58	2.06	3.45	5.08	3.96	1.92	-0.44
2M/PC/03	8.2	1280	0	9.10	2.17	3.52	3.56	4.22	2.24	2.02
2M/PC/04				------- Dry --------						
District : Pratapgarh										
2P/PC/01	8.1	673	0	4.80	0.40	1.32	2.12	2.38	1.81	1.36
2P/PC/02				------ Damaged ------						
2P/PC/03				------ Damaged ------						
2P/PC/04				------ Damaged ------						
District : Auriya										
2T-I/PC/01	8.6	637	0.51	3.50	2.13	1.98	2.32	1.56	1.06	-0.26
2T-I/PC/02				-------- Dry ----------						
2T-I/PC/03				-------- Dry ----------						
2T-II/PC/01				------ Damaged ------						
2T-II/PC/02	8.8	670	0.50	5.60	0.33	0.89	2.45	2.12	1.44	2.76

APPENDIX-I

GYPSUM REQUIREMENT

The amount of amendment required to reclaim a sodic soil is a function of the cation-exchange capacity (CEC), the desired change in ESP, the soil bulk density, and soil depth. When the CEC is expressed in mol/kg of soil, the needed calcium (expressed as mol/kg of soil) is simply the product of CEC and the desired change in ESP divided by 100. The amounts of gypsum, calcium chloride, or sulfur needed to exchange various amounts of exchangeable sodium from a 0.3-m depth of soil having a bulk density of 1.47 Mg/m^3 are given in Table II-A. The amount of amendment required for other soil bulk densities can be obtained by multiplying the values given in Table II-A by the ratio of the new bulk density to 1.47.

Table II-A

Exchangeable Sodium	Gypsum	Calcium chloride	Sulfur*
mol/kg of soil	Mg/ha		
10	3.8	2.4	0.7
20	7.6	4.9	1.4
30	11.0	7.3	2.1
40	15.0	9.8	2.8
50	19.0	12.0	3.5
60	23.0	15.0	4.2
70	27.0	17.0	5.0
80	30.0	20.0	5.7
90	34.0	22.0	5.7
100	38.0	24.0	7.1

*Applicable only if the soil contains sufficient lime with which the sulfur can react.

The amount of water that must pass through the profile for chemical reclamation with gypsum depends on the amount of gypsum needed for chemical exchange. For example, assume that the soil has a CEC of 150 mol/kg, a bulk density of 1.47 Mg/m^3, an ESP of 50, and that the average ESP is to be reduced to 12 (ΔESP

= 38) in the 1-m soil depth. Therefore, the desired exchange is [150 mol/kg x (50 - 12)]/100 or 57 mol/kg of soil. From Table II-A, 21.6 Mg/ha of gypsum are required for a soil depth of 0.3 m or 72 Mg/ha for a soil depth of 1 m. Typically, a 10-mm depth of applied water will dissolve about 250 kg of gypsum per hectare. For this example, 2.9 m of water would be required. Although, the average ESP after reclamation was assumed to be 12, the final ESP will be lower near the soil surface than at the bottom of the profile. Complete exchange by all the dissolved gypsum was also assumed for the calculation. In practce, complete exchange should not be expected. If a chemical amendment is required, it is generally recommended that the amount the be chemically equivalent to about 1.25 times the amount of exchangeable sodium that is to be removed (U.S. Salinity Laboratory Staff, 1955).

Schoover proposed a relationship between Exchangeable Sodium and Gypsum requirement, based on work of Mc George and Breazeale (1951):

For exchangeable sodium contents ranging from 0.1 to 12 m eq / 100 gm., Exchangeable Sodium (meq/gm) = 0.96 + 0.99 x Gypsum requirement (m eq/100 g.)

So, Gypsum requirement (meq/100 gm) = $\frac{Exchangeable\ Sodium\,(meq/100\,gm) - 0.96}{0.99}$

APPENDIX-II

GYPSUM SOLUBILITY

The activities of ions in a solution in equilibrium with a solid will be strictly determined by the solubility product constant of the solid. However, the soluble concentration of the ions will vary depending on the chemical properties of the solution. Three main factors will impact ion concentration under the condition of sold-solution equilibrium: (1) ionic strength effect, (2) ion coplexation or ion pairing, and (3) common ion effect. These factors are illustrated in the findings of Longneker and Lyerly (1959), which examine the influence of various salts, or background electrolytes, and their concentrations on gypsum [Ca $SO_4.2H_2O$] solubility. It is noted that solubility, as used in Table III-A, is defined as the concentration of the gypsum dissolved in the equilibrating solution, expressed as mmol L^{-1} of gypsum dissolved. This definition should not be confused with gypsum stability or solubility product, whic are thermodynamic characteristics of the mineral and not influenced by solution composition. The dissolution of gypsum and the associated K_{SP} (Soubility Product Constant) value are described by:

$$CaSO_4.2H_2O(s) \rightarrow Ca^{++}(aq) + SO^{--}(aq) + 2H_2O(l)$$

$$K_{SP} = (Ca^{++})(SO_4^{--}) = 10^{-4.62}$$

At equilibrium, the IAP $[= (Ca^{++})(SO_4^{--})]$ of a solution in contact with gypsum will always be $10^{-4.62}$

Table III-A

Salt Cocentration mmol L^{-1}	EC dS m^{-1}	Gypsum Solubility mmol L^{-1}	% of Solubility in H_2O
$CaCl_2$			
0	Pure H_2O	15.01	100.0
0.5	0.21	14.51	96.6
2.5	0.64	14.12	94.0
5	1.20	13.69	91.2
10	2.25	12.77	85.1
20	4.35	10.85	72.3
NaCl			
0	Pure H_2O	15.01	100

1	0.20	15.03	100.1
5	0.65	15.74	104.9
10	1.21	16.58	110.5
20	2.40	17.44	116.2
40	4.60	18.36	122.3
$MgCl_2$			
0	Pure H_2O	15.01	100.0
0.5	0.21	15.35	102.2
2.5	0.63	16.04	106.8
5	1.19	17.23	114.8
10	2.30	18.74	124.9
20	4.30	20.47	136.3

(Soil & Water Chemistry, Michael E. Essington, pp. 274-276)

Table III-A shows that gypsum solubilty (the amount of gypsum dissolved) decreases with increasing $CaCl_2$ concentration. Considering the gypsum dissolution reaction above, the reaction is controlled by the solublity product constant which states that at equilibrium the the product of calcium ion activity and sulfate ion activity is a constant value.

If one adds Ca to the solution, as in this case by the addition of $CaCl_2$, one is adding a reaction product to the system (increasing the activity of Ca^{++}). This forces the chemical reaction to move to the left and results in gypsum precipitation (or gypsum dissolution). This is called the common ion effect, where calcium is a common ion in the gypsum dissolution reaction. A similar result is observed when Na_2SO_4 is added to solution in equilibrium with gypsum. Indeed, increasing the concentration of a common ion decreases the Ca SO_4 concentration in the equilibrium solution but has no impact on IAP of gypsum.

In an NaCl system, gypsum solubility increases with salt concentration. This result is explained by the ionic strength effect. As the salt content of the equilibrium solution increases, so does the ionic strength of the solution. As ionic strength increases, activity coefficients decreases, as do activities of Ca^{++} and SO_4^{--}. Since the solubility product (K_{SP}) for gypsum is constant and is numerically equal to the product of Ca^{++} and SO_4^{--} activities: $(Ca^{++})(SO_4^{--})$, a decrease in Ca^{++} and SO_4^{--} activities would result in more gypsum dissolution to return the solution to the equilibrium state.

Increasing the concentration of $MgCl_2$ results in an increase in gypsum solubility, similar to that observed in the NaCl system. Clearly, the ionic strength effect has a significant influence on gypsum solubility in the $MgCl_2$ system. However, more gypsum dissolves in the $MgCl_2$ systems than in comparable ionic strength in NaCl system. A 20-mmol L^{-1} of $MgCl_2$ results in a 36.3% increase in gypsum solubility compared with a 22.3% increase in the 40 mmol L^{-1} system. We have established the fact that the ionic strength effect is active in both the $MgCl_2$ and NaCl systems. In the NaCl systems, the only significant aqueous complexation is the formation of the $CaSO_4^0$ species. Neither Na nor Cl substantially contributes to ion pair formation in these systems. However, the presence of Mg results in the formation of an additional ion pair: $MgSO_4^0$. By virtue of this reaction, some of SO_4^{--} is removed from the solution (into the soluble $MgSO_4^0$ species), forcing more gypsum to dissolve to maintain the K_{sp}. This ion pairing or complexation effect has the opposite impact of the common ion effect on mineral solubility.

APPENDIX-III

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