Historical Perspectives and Dynamics of Nature, Extent, Classification and Management of Salt-affected Soils and Waters

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Abstract

Soluble salts are a natural feature of the landscape, being present usually in small amounts in all soils, waters and rocks. It is only their accumulation beyond a certain proportion that creates a salt land. Soil salinization is an *in situ* form of soil degradation that arises due to the buildup of soluble salts to deleterious levels at or near the soil surface. Being one of the oldest environmental problems, salinization has been considered as 'one of the seven main paths to desertification' and a major process of land degradation. Salt-affected soils occur in about 100 countries under different environmental conditions and have diverse morphological, physical, chemical, physico-chemical and biological properties, but one common feature, the dominating influence of electrolytes on the soil-forming processes, joins them into one family. There are many classification systems for salt-affected soils, while a large number of systems exist in individual countries, particularly in those where salt-affected soils are common. Saline soils develop mainly under the influence of sodium chloride and sulphate and closely associated with deserts and semiarid regions and seldom occur in subhumid and humid regions. Alkali soils, formed under the influence of sodium ions capable of alkaline hydrolysis, occur mainly in semiarid, subhumid and humid regions, but they can also be found under practically any environmental conditions.

Beneath many of the world's deserts are reserves of saline water, and the information for saline water use for irrigation on global perspective is reported from about 50 countries. FAO has also published the standard water quality criteria for saline irrigation. To meet the requirement of good-quality water, for

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J. C. Dagar et al. (eds.), *Research Developments in Saline Agriculture*,
https://doi.org/10.1007/978-981-13-5832-6_1

drinking and other uses of ever-increasing population, will make the use of poor-quality waters inevitable. The concerted research efforts have shown that the degraded salt-affected lands and poor-quality waters can be put to sustainable productive use by adopting suitable strategies and remunerative alternate uses through agroforestry adopting appropriate planting and management techniques. In the present chapter, a brief historical perspective and dynamics of nature, extent, classification and management aspects of salty soils and waters have been dealt in brief.

Keywords
Salt-affected soils · Saline soils · Alkali/sodic soils · Secondary salinization · Historical perspectives · Reclamation measures · Poor-quality waters

1.1 Introduction

Salts are not alien to the land. Soluble salts are a natural feature of the landscape, being present usually in small amounts in all soils, waters and rocks. It is only their accumulation beyond a certain proportion that creates a salt land. Under certain conditions, these salts accumulate through a process called salinization. Soil salinization is an *in situ* form of soil degradation that arises due to the buildup of soluble salts to deleterious levels at or near the soil surface (Schofield et al. 2001). Being one of the oldest environmental problems, salinization has been considered as 'one of the seven main paths to desertification' (Kassas 1987) and a major process of land degradation (Thomas and Middleton 1993). Salt-affected soils occur under different environmental conditions and have diverse morphological, physical, chemical, physico-chemical and biological properties, but one common feature, the dominating influence of electrolytes on the soil-forming processes, joins them into one family (Szabolcs 1979). A certain concentration of electrolytes determines not only the morphology of the soil profile, but also other properties which result, as a rule, in low fertility and limited agricultural value on land affected by salinity (Szabolcs 1989).

Beneath many of the world's deserts are reserves of saline water. The major occurrences of saline waters are in the Thar Desert of the Indian subcontinent, the Arab Desert of the Middle East countries, the Sahara Desert in North Africa, the Kalahari Desert in Southern Africa, the Atacama Desert in South America, the California Desert in North America and the West Australian Desert. The information for saline water use on the global prospective is reported from about 50 countries, which are using saline water for irrigation in one or other forms. These countries are virtually from the semiarid and arid regions, except some developed nations, which make use of the wastewater for irrigation. Rhoades et al. (1992) reported the use of saline water in irrigation in many countries. With increasing demands of agricultural produces and other necessities for ever-increasing population and limited availability of good-quality water, saline water irrigation is now considered as an imperative necessity for the sustainable agricultural development, which includes the use of saline groundwater, saline drainage water and sewage for irrigation.

In the present chapter, an attempt has been made to compile information on historical perspectives of nature, classification and management issues of salt-affected soils and also judicious use of saline water both groundwater and seawater by applying modern technologies for agricultural production.

1.2 Natural Incidences of Salinity (Historical Perspectives)

Salinity has been existing with mankind since the beginning of agriculture. Though its existence has been always ecologically important in arid and semiarid regions of the world, the adverse effects of the problem were realized only when it staked the food and nutritional security of the population. Many authors have described the consequences of the extension of salinity, which has developed in the irrigated areas of the world due to primitive or incorrect technologies (Thorne and Peterson 1954; Jacobsen and Adams 1958; Hobbs and Russell 1967; Talsma and Philip 1971; Szabolcs 1986, 1989). It is well known that in ancient Mesopotamia, an area of fertile soils between the rivers Tigris and Euphrates, quantities of grain and other crops sufficient to feed large population were produced for a long time. In modern times, this area has been known only as a bare desert. It is also well known that in ancient China, in the Indus Valley (Dregne 1967) and in South America, vast territories were turned into deserts because of salinity problems resulting from faulty irrigation by ancient societies. The problem of secondary salinization runs through the whole history of mankind (Balba 1976). Jacobsen and Adams (1958), while explaining progressive changes in soil salinity in ancient Mesopotamian agriculture, stated that as to salinity itself, three major occurrences were established from ancient records: (i) The earliest of these, and the most serious one, affected southern Iraq from 2400 BC to at least 1700 BC; (ii) a milder phase attested in documents from central Iraq written between 100 and 900 BC; and (iii), lastly, there was archaeological evidence that the Nahrwan area east of Baghdad became salty only after 1200 AD. Several parallel lines of evidences allow the ensuing salinization to be followed quantitatively. For example, crop choice could be influenced by many factors, but the onset of salinization strongly favoured the adoption of crops which were more salt-tolerant. Counts of grain impressions in excavated pottery from sites in southern Iraq of about 3500 BC, made by H. Helbaek (cited by Jacobsen and Adams 1958), suggest that at that time the proportions of wheat and barley were nearly equal. A little more than 1000 years later, in the time of Entemenak at Girsu, the less salt-tolerant wheat accounted for only one-sixth of the crop. By about 2000 BC, the cultivation of wheat accounted for less than 2% of the crop in the same area, and by 1700 BC, the cultivation of wheat had been abandoned completely in the southern part of the alluvium. Further, concurrent with the shift to barley cultivation was a serious decline in fertility which for the most part could be attributed to salinization. At about 2400 BC in Girsu, the yield was respectable and comparable to the Canada and USA standards, but the same declined by 43% by 1700 BC and further deteriorated to one-third of the initial. The southern part of the alluvial plain appears never to have recovered fully from the disastrous general decline in fertility which accompanied the salinization process.

Tracing the history of salinity in the Indian subcontinent, Singh (1998a) reported that in ancient India, between 2500 BC and 600 AD, soils were known as *urvara* (fertile) and *anurvara* (desert); however, salinity was recognized as a potential threat to agriculture only during the middle of the nineteenth century. Now, there is an increased awareness about secondary salinization in irrigated command areas. In north and north-western India, salt-affected soils were known as *kallar*, *usar* or *reh* even before the arrival of the British, but the earliest recorded evidence of the presence of *usar* and indigenous methods of its reclamation in the united provinces of Agra and Oudh finds mention in the 1850 tour diary of Mr. Sleeman (Moreland 1901). He mentioned that farmers used to irrigate, manure, cross plough and flood *usar* fields for two to three consecutive seasons for reclamation; nevertheless, the soil was liable to become *usar* if neglected or left fallow for a few years. Sleeman's diary also suggested that reclamation of salt-affected soils using different methods was practised in the united provinces much before any scientific research had been conducted. The Director of Land Records and Agriculture correspondence of 1888 informed that about 12.72 million ha of area was affected by *usar* in north-western provinces and Oudh. Later, Tiwari et al. (1989) also reported similar extent of alkali lands in Uttar Pradesh. Leather (1897) further gave account of the vast extent, poor cultivation conditions and economic loss due to *usar* or *reh* land problem in plains of northern India. His account also suggested serious concerns of the government of North-western Province and Oudh for understanding and managing the problem. The problem was not restricted only to united provinces of Agra and Oudh and North-western Province, but the Indus plains of Punjab also suffered from soil salinity before introduction of any large-scale canal irrigation. Dr. Jameson, superintendent of the Botanical Gardens, during his visit of Punjab soon after annexation of the 'Sikh state' by the British in 1849, recorded that large area in Kapurthala (~77 km^2) lied barren due to want of water and soil salinity (Jameson 1852). The extent of the problem in Punjab can be understood by a communication in 1865, of an X-En of Punjab Irrigation Department, mentioning that 'whole of the country in Punjab lying west of Jamuna is impregnated with *reh* i.e. salts in soil and water in the proportions from traces to absolutely injurious to all vegetation'. Whitecombe (1971) reported development of variable-size patches of the *reh* efflorescence that increased westwards in the Barh, from Lahore to Multan and Shahnoor and from either of the places to the Derajat and foot of the Soolimani mountain.

The widespread problem of salt-affected lands also existed in Sind part of the Indus plain. It is evident from the government of India's call of 1906 asking experienced local irrigation and revenue officers for reports on the problem of *kallar* or *alkali* in Sind. The commissioner of Sind reported that extent and gravity of the problem could not be judged due to non-availability of any statistics and materials even for a rough estimate of any degree of reliability. As per reports of Henderson (1914) the saline area occurred from isolated patches to continuous many miles barren tract in Sind. He further suggested that the gravity of the problem cannot be measured only by ‘the domination in the cultivated area and the injury to the crops in localities where attempts are being made to control it but only the permanent exclusion from cultivation of large areas of otherwise valuable lands’.

1.2.1 Secondary Salinization Due to Irrigation

The expansion of irrigation not only resulted in more areas being irrigated but also affected the properties of the soils. Although the irrigation dates back to prehistoric times, its rapid development only started about in the beginning of the nineteenth century. It is clear from the fact that the global area of irrigated land grew from 8 million ha in 1800 to 48 million only in 1900 and was more than doubled by the next 75 years (Szabolcs 1989) and ultimately reached 310 million ha, out of which 117 million ha (38%) is irrigated with groundwater (FAO 2012). The main reservoir of saline water in arid and semiarid regions is the groundwater. The soluble salts accumulated in the groundwater, as a result of the geochemical processes, can cause salinity problems when this groundwater is used for irrigation. As long as groundwater table is deep and the moisture cannot come up through capillary flow to the rootzone soil profile, even saline groundwaters do not induce immediate salinization. As the effect of irrigation, the groundwater table may rise so high that it can reach the surface layers and cause salinization even when good-quality water is used for irrigation.

The natural or artificial drainage of irrigated land, or land to be irrigated, is also a major factor in the processes of secondary salinization. The irrigation was practised for thousands of years in the Nile Valley under the dry climate without any secondary salinization, but because of the introduction of perennial irrigation during the nineteenth century in Egypt, due to the change in salt and water regime, the Nile Delta became salinized, and an artificial drainage system became necessary to get rid of excess salts (El-Gabaly 1972). Thus, with the exception of places with good natural drainage, which is rather rare, in arid and semiarid regions, the lack of artificial drainage leads to secondary salinization, and as many as half of the existing irrigation systems of the world are more or less influenced by secondary salinization, alkalization and waterlogging (Szabolcs 1989).

Singh (1998a) also reported the development of secondary salinization due to irrigation in the Indian subcontinent. According to him the first official notice of land degradation due to the introduction of canal irrigation was lodged in 1855 by a farmer of ‘Moonak’ village in command of western Yamuna canal since its construction by Feroze Shah Tuglaq in the fourteenth century and remodelled by the British in 1839. The then British government, who planned a number of large irrigation projects in the country, took urgent action on understanding the causes and possible remedies to remove such fears of farmers. This is evident from probably the first selected correspondence records of the government, published in 1864, relating to the deterioration of lands in the command of western Yamuna canal leading to the development of soil salinity due to canal irrigation. The correspondence mainly dealt with the effects of canal on soil saturation but also described its role in alkali soil formation (Moreland 1901). Likewise, secondary soil salinization due to canal irrigation was also noticed in the peninsular India. Mann and Tamhane (1910) reported the appearance of barren, salt-encrusted spots, within 5 years, in some of the best and deepest soils in the command of Nira Valley irrigation canal opened first in 1884 to introduce large-scale irrigation in deep black soils. Development of salinization caused anxiety among farmers and the irrigation authorities. Based on analysis of soil samples, Dr. Leather (1893) reported that the salt lands were increasing rapidly, but the problem did not receive proper attention during the initial years. The matter ultimately got the needed attention in 1903 when a committee composed of Messrs Vishveshvaraya, PR Mehta and JB Knight was appointed to consider the issue. According to Mann and Tamhane (1910), it was the 1905 report of the above committee that received the most careful consideration of the situation up to that time. The committee recommendations issued as Resolution No. 8968 of the Revenue Department suggested the following (Singh 1998b):

1. Opening *nadies* (drainage) in the neighbourhood of low-lying lands affected by waterlogging and salt efflorescence
2. Measurement of affected survey numbers and their portions with remarks about their condition
3. Request to the agricultural department to observe the lands requiring improvement by the farmers and advise them in reclamation work

The government approved these recommendations, and the follow-up work was entrusted to the survey and agricultural departments.

1.3 Classification, Distribution and Characteristics of Salt-affected Soils

1.3.1 Classification

There are many classification systems for salt-affected soils. Some of these are incorporated into the generally accepted world soil classification systems, such as soil taxonomy, the classification system of the former USSR, the soil classification system of the FAO/UNESCO Soil Map of the World, Soil Map of Europe and many others. A large number of systems exist in individual countries, particularly in those where salt-affected soils are common; and there are local names and terms for different kinds of salt-affected soils in such countries, and it becomes difficult to find out correlation, if any, between them. Szabolcs (1989) has summarized the tentative correlation between the most widely used classification systems of these soils. At least five groups of salt-affected soils are influenced by different chemical types of electrolytes (Table 1.1). Saline soils developing mainly under the influence of sodium chloride and sulphate are closely associated with deserts and semiarid regions and seldom occur in subhumid and humid regions. These are the most widespread types of soils on the continents and, with the exception of Europe, are dominant within soil family. Alkali soils formed under the influence of sodium ions

Table 1.1 Grouping of salt-affected soils

Electrolytes causing salinity and/or alkalinity	Types of salt-affected soils	Environment	Main adverse effect on production	Method for reclamation
Sodium chloride and sulphate (nitrate in extreme cases)	Saline soils	Arid, semiarid	High osmotic pressure of soil solution (toxic effect)	Removal of excess salts through leaching
Sodium ions capable of alkaline hydrolysis	Alkali soils	Semiarid, subhumid, humid	Alkali pH, effect on water and soil physical properties	Lowering or neutralizing the high pH by chemical amendments
Magnesium ions	Magnesium soils	Semiarid, subhumid	Toxic effect, high osmotic pressure	Chemical amendments, leaching
Calcium ions (mainly $CaSO_4$)	Gypsiferous soils	Semiarid, arid	Acid pH, toxic effect	Alkaline amendments
Ferric and aluminium ions (mainly sulphates)	Acid sulphate soils	Seashores, lagoons with heavy sulphur-containing sediments	Strong acidic pH, toxic effects	Liming

Source: Szabolcs (1989)

capable of alkaline hydrolysis occur mainly in semiarid, subhumid and humid regions, but they can also be found under practically any environmental conditions, from the polar circle to the equator including at different altitudes from sea level to high mountains. Szabolcs (1989) has also recognized magnesium, gypsiferous and acid sulphate soils as important salt-affected soils.

Attempts were made to classify the soils on the basis of total soluble salts measured in terms of electrical conductivity of the soil saturation paste extract (ECe) or various dilutions (soil/water 1:2 or 1:5), exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR) and pH of the saturation paste (pHs) or other dilutions. The US Salinity Laboratory Staff in 1954 (USSL 1954) originally proposed the three categories of salt-affected soils on the basis of these parameters i.e. saline, saline-alkali and alkali soils. The definitions in respect of these three categories were slightly modified later by Soil Science Society of America (SSSA 1987). It was described that owing to excess salts (ECe 4 dS m^{-1} or 2 dS m^{-1} later on) and absence of significant amount of sodium (ESP 15), saline soils are generally flocculated, and as a consequence their conductivity is equal to or even greater than their nonsaline counterparts. A saline-alkali soil (ECe 4 dS m^{-1} or more; ESP 15 or more) was described similar to that of saline soils as long as sufficient salts are present, whereas upon leaching, these soils become alkaline (pH 8.5) leading to dispersion, and their permeability reduces to levels those affecting crop growth. The term ‘alkali’ was discarded later on to be replaced with ‘sodic’, and these soils contain sufficient exchangeable sodium (ESP 15) to affect the physical behaviour of soils and interfere with growth of the most of the crops.

Table 1.2 Classification of salt-affected soils under two systems

Soil group	Soil map of world (FAO/ UNESCO Project)	Soil classification (Soil Survey Staff 1975)
Saline soils	Solonchak	Salorthids
Alkali soils		
Without structural B horizon	Orthic solonchak	Salorthidic-calcuiustolls
	Mollic solonetz	Salorthidic-haplustolls
	Takyric solonchak	Halaquepts
	Gleyic solonchak	
With structural B horizon	Solonetz	Nadurargids, Natrargids, Natriboralfs, Natrudalfs, Natrustalfs, Natrixeralfs
	Orthic solonetz	Natralbolls, Natriborolls, Natrustolls
	Mollic solonetz	Natrixerolls, Nartaquolls
	Gleyic solonetz	Natraqualfs
	Solodic planosols	Argiabolls

Source: Sharma (1998)

The Indian classification of salt-affected soils is also based on the above criteria, but in place of three categories of salt-affected soils (saline, sodic and saline-sodic), these soils were classified into two groups based on the nature of plant responses to the presence of salts and the management practices desired for their reclamation. Abrol and Bhumbla (1978) concluded that 'the so-called saline-sodic soils' are in fact of rare occurrence, and only two categories 'saline' and 'sodic' were recognized.

Soil taxonomy (Soil Survey Staff 1975) and the World Soil Map Legend (FAO-UNESCO 1974) are the two internationally accepted systems of classifying the soils (Table 1.2). A feature common to both is the use of defined diagnostic horizons in different classes.

The existence of salt-affected soils in India, called *usar* (Raychaudhuri and Govindarajan 1970), has been reported since ancient times (2500 BC). Under the genetic system of soil classification, these soils were classified as *solonchak* or *solonetz* (Sharma 1998). The soil taxonomy has six categories which are grouped as higher categories, namely, order, suborder and great group, and another one is lower categories, namely, subgroup, family and series. Twelve orders have been recognized. Each order is distinguished due to strictly defined diagnostic horizons. In salt-affected soils of India, the most common epipedon (surface diagnostic horizons) is ochric, and the subsurface horizons are argillic, natric, cambic, calcic, gypsic and salic (Table 1.3) as described by Sharma (1998).

According to the soil taxonomy, the important and extensively occurring salt-affected soils of India are classified as:

Natraqualfs: These have a natric subsurface horizon and a perched water table, existing in canal command areas of the Indo-Gangetic plains.

Natrustalfs: These have a natric subsurface horizon and occurred in areas with rainfall <550 mm.

Natrargids: These exist in western parts of the country under arid climate.

Table 1.3 Characteristics of surface and subsurface horizons commonly existed in salt-affected soils

Sl. no.	Name of surface and subsurface horizon	Characteristics
1.	Ochric epipedon	This horizon is light in colour and have organic matter <1%. The horizon is hard or very hard when dry and does not qualify for any other horizon
2.	Argillic horizon	This is an illuvial horizon where substances leached and transported from an overlying eluvial horizon have been deposited over many years. This horizon must have more total and finer clay than the overlying horizon
3.	Natric horizon	It is an argillic horizon with either prismatic or columnar structure or with ESP >15 and has more exchangeable sodium plus magnesium than exchangeable calcium
4.	Cambic horizon	This is a horizon showing alterations in colours and textures in the neighbouring horizons, brought about by operative soil processes. This alteration is not definitive to qualify for any other diagnostic horizons
5.	Calcic horizon	This is a horizon of accumulation of more than 15% calcium carbonate
6.	Gypsic horizon	A horizon with enrichment of secondary sulphates
7.	Salic horizon	It contains secondary enrichment of water-soluble salts. The salt should be at least 2% in the horizon, and the product of its thickness (cm) and salt (% by weight) is $\geq$60

Some soils are also classified under Calciorthids, Camborthids and Salorthids (highly saline soils, mostly in the coastal regions). The suborders Psamments, Fluvents and Orthents may have salt-affected soils. Great groups Halaquepts and Ustochrepts have salt-affected soils, while the other great groups, Chromusterts and Pallusterts, may have salinity or alkalinity in the medium and deep black soils. According to soil taxonomy, almost all the saline and alkali soils can be classified. However, some of the crucial properties in surface horizons of these soils like high ESP and/or EC and criterion for Salorthids are not appropriately explained in the classification (Sharma 1998).

1.3.2 Distribution

Looking at some of the recently modified classifications in the world literature, salt-affected soils are found distributed in all the continents covering about 954.83 million ha (Mha) in about 100 countries, which is about 10% of the total surface of dry land (Szabolcs 1989). As per recent FAO/UNESCO Soil Map of the World (FAO 2008), the total salt-affected area is 835 Mha, out of which 397 Mha are saline and rest sodic soils. Distribution of salt-affected soils excluding magnesium and acid sulphate soils along with countries of occurrence is depicted in Table 1.4.

Table 1.4 Global distribution of salt-affected soils (million ha)

		Area (Szabolcs 1989)	Area FAO (2008)
Continent and/or subcontinent	Countries (Szabolcs 1989)[a]	(million ha)	(million ha)
North America	Canada, USA	15.75	20.0
Mexico and Central America	Mexico, Cuba, Haiti	1.97	
South America	Argentina, Bolivia, Brazil, Chile, Columbia, Ecuador, Paraguay	129.16	112[b]
Africa	Afars and Issas Territory, Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Chad, Cameroon, Egypt, Ethiopia, Gambia, Ghana, Guinea, Kenya, Liberia, Libya, Malagasy Republic, Mali, Mauritania, Morocco, Niger, Nigeria, Senegal, Sierra Leone, Somalia, South West Africa, Sudan, Tanzania, Tunisia, Zaire, Zambia, Zimbabwe	80.54	73
South Asia and the Middle East	Afghanistan, Bangladesh, Burma, India, Iran, Iraq, Israel, Jordan, Lebanon, Kuwait, Muscat and Oman, Pakistan, Qatar, Sarawak, Saudi Arabia, Sri Lanka, Syria, Tanzania, the Trucial States, Turkey, Yemen, the People's Democratic Republic of Yemen	87.61	444[c]
North and Central Asia	China, Korea, Mongolia, Solomon Islands, the USSR (undivided)	211.69	106[d]
South-East Asia	Indonesia, Cambodia, Malaysia, Thailand, Vietnam	19.98	
Australasia	Australia, Fiji	357.33	
Europe	Austria, Bulgaria, Czechoslovakia, Cyprus, France, Greece, Hungary, Italy, Portugal, Romania, Spain, USSRI (partly), Yugoslavia	50.80	80
Total		954.83	835

[a] Does not include magnesium and acid sulphate soils
[b] Mentioned under Latin America
[c] Asia, the Pacific and Australia
[d] Near East

1.3.3 Genesis and Characteristics of Salt-affected Soils

The mineralogical composition of soil, including relative amounts of primary and secondary minerals, is determined by geological processes, the make-up of the parent materials, the intensity of weathering and duration of weathering in the existing soil or the soils that served as parent material for the present soil. Szabolcs (1989) described the genesis of salt-affected soils of many countries showing the effects of relief, mineralogy and climate in different countries. Geologically the

Indian subcontinent is divided into two parts, viz. Peninsula (south of Vindhyans) and the extra-peninsula (mountainous region of Himalayas). Surprisingly, the Peninsula constituting the central and the southern states has been a land area, which since the origin of earth has never been submerged beneath the sea; on the contrary, the extra-peninsula, constituting the northern states of India and the adjacent Pakistan, remained under the saline waters of the sea for greater part of the earth history and has thus been covered by successive marine deposits (Wadia 1979; Raj-Kumar 1998). The greater Indo-Gangetic plains are formed mainly from alluvial deposits of the Indus and Ganges rivers borne down from extra-peninsula, which earlier remained under saline waters of the Tethyan sea. Therefore, there is a basic difference of geology and mineral composition of the northern and southern parts of the subcontinent. Raj-Kumar (1998) has dealt with clay mineralogy of salt-affected soils in detail.

Oceans are the biggest storehouse of salts on the earth's surface. The seawater has 42×10^{15} Mg of dissolved salts, of which 85.65% is sodium chloride. Though the early seas had a very small volume and the water was changed mainly with carbonates of alkali and alkaline earths, the release of huge amounts of water vapours, chlorine and other volatiles from degassing of earth's interior and mantle led to its enrichment with sodium chloride. This happened 100 to 600 million years ago, and since then the seawater is supposed to have maintained composition similar to that prevailing today (cited by Dhir 1998). The rivers on the earth deliver annually 3.85×10^{12} kg soluble salts to the oceans. Of this, the entire sodium chloride content is believed to be cyclic, i.e. goes to land via sea sprays and atmosphere from the oceans, but excess of sodium and rest of the salts owe their origin to the continents (Dhir 1998). However, while the sea is receiving a continuous load of salts from the land, it is also losing it at the same rate through precipitation and other processes, giving seawater more or less the same composition. The rocks and the constituent silicate minerals form the original source of salts on the continents and the oceans. Though 75 to 85% of the igneous rocks are made up of the oxides of silicon, aluminium and iron, the rest are mainly made up by oxides of calcium, magnesium, sodium and potassium. Each of these alkali and alkaline earth elements is present in the range of 2–3% with basalts being in greater abundance of calcium and magnesium and syenites of that of sodium. The elements are concentrated in feldspars and ferro-magnesium minerals.

The previous investigations by several workers (Medlicott 1863; Center 1880; Leather 1914) on *usar* lands of the Indo-Gangetic alluvial plain suggested weathering as a source of presence of salt in these soils. The primary minerals present in the sodic and non-sodic soils of the Indo-Gangetic alluvial plain contain quartz, feldspars (orthoclase and plagioclase), muscovite, biotite, chloritised biotite, tourmaline, zircon and hornblende in their sand fractions (Goswami 1979; Bhargava et al. 1980; Sidhu and Sehgal 1978). Similar types of mineralogy possibly represent the prevalence of plagioclase feldspar in the soils forming part of the alluvium in Punjab (Sidhu and Sehgal 1978; Pundeer et al. 1978).

Studies conducted by several researchers (Agarwal and Mehrotra 1953; Mehrotra 1968; Bhargava et al. 1972; Bhumbla et al. 1973; Sehgal et al. 1973; Bhargava et al. 1980) revealed that the alkali soils occur in micro-depressions of the Indo-Gangetic alluvial plain. Auden et al. (1942) also listed some factors which are responsible for synthesis of the sodium salts such as (a) alternate dry and wet seasons, (b) very gentle slope gradients, (c) rocks rich in soda minerals, (d) quality of ground and canal water, (e) base-exchange reaction and (f) prevailing high water table. First three factors have been justified later by Bhargava et al. (1980), who documented that the weathering of aluminosilicate minerals and the factors of microrelief along with climate inducing seasonal flooding and evaporation of the deposited run-off wash played a significant role in the formation and spreading of alkali soils in the form of local stretches within the micro-depressions.

In the total area of the Indo-Gangetic alluvial plain, alkali soils generally occurred in areas with mean annual rainfall ranging from 550 to 1000 mm (Bhargava and Abrol 1978; Bhargava et al. 1980). Alkali soils in Punjab and Haryana zone mostly occurred in an *ustic* soil moisture regime, however, due to the occurrence of a shallow fluctuating water table, the alkali soils also found existing in an aquic and para-aquic moisture regime in Uttar Pradesh. Some leaching and illuviation processes happen in these soils due to marginal surplus of precipitation over the evaporation, consequences of which lead the formation of illuvial B horizon (Bhargava et al. 1980). The existence of illuvial B horizon has been verified by the occurrence of argillans on ped faces and predominance of finer clay in B horizon, the fine/total clay ratio and existence of clay cutans on ped faces (Sharma 1979; Bhargava et al. 1980). Another effective part played by the predominant climate is to facilitate evaporation of the run-off deposited in the micro-depressions from June to October.

The highly sodic conditions of alkali soils bring about degradation of the clay minerals as noticed by the tendency of differences in molar ratios of amorphous SiO_2 and Al_2O_3 in alkali soil profiles from Uttar Pradesh. Degradation is highest in the surface horizon, declining with depth which is in accordance with the degree of sodium saturation. The geomorphic setting and the physical, chemical and hydrological characteristics of alkali soils establish that these have originated during the direct process of sodiumization beginning firstly at the surface and not through the sequential processes of salinization, alkalization and desalinization (Sharma 1998; Sharma and Bhargava 1981).

Bhargava et al. (1980) and Bhargava and Bhattacharjee (1982) attributed alkaline hydrolysis of feldspars in the upland plains for the origin of soluble salts, which got transported through surface and subsurface flow to sodium spoils and groundwaters in the plains down the gradient. Raj-Kumar (1992), however, contradicted the hypothesis and observed the occurrence of sodic soils and sediments not only on the source area itself but also further up in the Sivalik Hills. Therefore, the salts might have come from further up (Himalayas) and specifically from the marine formations and salt-spring found therein. He further surmised that feldspar weathering was not possible at the prevailing pH of the soils; hence, the sodium carbonate could have come from the reaction of sodium chloride of run-off water with calcareous rocks.

Saline soils occur under different geomorphic and climatic conditions in different parts of the country because different cycles play the most significant role in accumulation of excessive amount of salts in soils. The characteristics of broad groups of saline soils in India, viz. inland, coastal and deltaic saline soils, are discussed by Sharma (1998) below.

1.3.3.1 Inland Saline Soils of Arid and Semiarid Regions

Highly saline soils containing excessive amount of neutral salts are prevalent in the arid to semiarid parts of Punjab, Haryana, Rajasthan and Gujarat. These soils occur in areas receiving $<$ 550 mm mean annual rainfall. Under extremely desiccating conditions, the maximum salts accumulate in the surface horizon. These soils comprise a shallow saline water table and frequently remain waterlogged or even became submerged for some duration in every year. Characteristics of a saline soil with saline and shallow water table are depicted in Table 1.5.

1.3.3.2 Saline-Alkali Soils of Indo-Gangetic Alluvium

The alkali soils are widely spread in the micro-depressions in the parts of Indo-Gangetic alluvial plain and studied well and characterized by several pioneers (Medlicott 1863; Center 1880; Leather 1914; Auden et al. 1942; Agarwal and Mehrotra 1953; Agarwal and Yadav 1954; Govindarajan and Murthy 1969; Kanwar and Bhumbla 1969; Sharma 1979). The most important characteristics of a typical alkali soil pedon are (a) an ochric epipedon with soil matrix and mottle colours in the hues of 2.5 Y or 10 YR; (b) high values and chromas; (c) textural gradation from sandy loam in the epipedon to clay loam or clay in the B horizon; (d) platy structure in a few surface centimetres followed by subangular/angular blocky structure below, ultimately turning massive in the calcic horizon usually about 1 metre deep; (e) presence of Fe/Mn concretions in the B horizon (normally throughout the depth above the calcic horizon); (f) very low organic matter status, decreasing gradually with depth; (g) preponderance of carbonates and bicarbonates of sodium; (h) gradual decrease of ECe, pH, ESP and SAR with depth; (i) low to very low infiltration characteristics; and (j) occasional presence of fluctuating, good-quality, shallow underground water table (Bhargava and Abrol 1978).

These soils exist, mostly in regions where mean annual rainfall is ~ 550 to 1200 mm, in the form of a narrowband separating the saline and alkali soils. These soils have a predominance of neutral salts and, however, also have sizable amount of sodium carbonates and bicarbonates. These are sandy to loam in texture and may contain a calcic or a petrocalcic horizon in the subsurface. The most of the alkali soils in this region are with dominant anionic composition of dissolved salts as $CO_3 + HCO_3 > Cl = SO_4$. Among the cations, sodium is by far the most dominant,

Table 1.5 Saline soil underlain by saline groundwater from Kalayat, district Jind (Haryana)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CO_3^{2-} + HCO_3^- (meq L^{-1})	Cl^- (meq L^{-1})	SO_4^{2-} (meq L^{-1})	Na^+ (meq L^{-1})	Ca^{2+}+Mg^{2+} (meq L^{-1})	$CaCO_3$ (%)
0–14	7.8	65.5	7	2.3	588	95.0	538	89.0	0.4
14–29	7.6	18.1	8	2.0	146	42.0	151	47.0	Nil
29–67	7.7	9.4	8	1.5	72	24.5	75	20.5	0.3
67–105	7.6	8.0	7	1.8	61	25.0	49	35.2	1.6
105–140	7.7	5.0	8	3.0	30	15.5	36	16.5	0.8

Source: Bhargava (1989)

and sodium adsorption ratio (SAR) of saturated extract is often in the range of 20 to 70 mmol L^{-1}. The mean profile ECe is highly variable, mostly in the range of 2–10 dS m^{-1} (Bhargava 1989). The saline-alkali and saline soils have higher-profile salinity and have generally NaCl and occasionally Na_2SO_4 as the dominant salt.

Weathering of aluminosilicate minerals during carbonation released solutions of bicarbonates and carbonates of alkali besides colloidal form of silica and alumina. The amount of sodium release increases in rate at temperatures greater than 25 °C. The bicarbonates and carbonates of alkali migrate along with subterranean and surface waters and deposited in undrained region under semiarid climatic conditions to form alkali soils (Kovda 1964).

$$\begin{aligned}
&\text{Na-primary mineral} + \text{HOH} \rightarrow \text{H-silicate clay} + \text{NaOH}\\
&\text{H-silicate clay} + \text{HOH} \rightarrow \text{Al}_2\text{O}_3.\text{H}_2\text{O} + \text{H}_2\text{SiO}_3\\
&\text{NaOH} + \text{CO}_2(\text{air}) \rightarrow \text{NaHCO}_3\\
&\text{NaHCO}_3 \rightarrow \text{Na}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O}
\end{aligned}$$

1.3.3.3 Inland Saline Soils of Subhumid Region

Large area of subhumid parts of north Bihar has experienced secondary salinization under the influence of continental climate and anthropogenic cycles. These soils are prevalent in parts of East Champaran, West Champaran, Saron, Muzaffarpur and Saharsa districts and developed on dolomitic alluvium having 23 to 40% calcium and magnesium carbonates in fine form. Though neutral salts dominate in these soils, some saline-alkali nature soils also have sizable content of sodium carbonate and bicarbonate.

1.3.3.4 Inland Salt-affected Medium and Deep Black Soils (Vertisols)

The medium and deep black soils (Vertisol) are widespread in parts of Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Gujarat and Karnataka. All Vertisols have the possibility to turn into saline, alkali or saline-alkali, and all these may occur within a small geographical area. The processes of salinization and alkalization are linked with rising water table successive to installation of canal irrigation in Vertisols. Montmorillonitic (smectite) clay mineralogy and high amount of clay content impart adverse physical characteristics to these soils.

1.3.3.5 Medium to Deep Black Saline Soils of Deltaic and Coastal Semiarid Region

Saline Vertisols with shallow water table existing generally within 1 metre depth in the deltas of the Godavari and Krishna rivers and along the Saurashtra coast in Gujarat. These soils usually have only neutral salts, with very small amount of bicarbonates. Smectite clay mineralogy and high content of clay create problems comparable to the inland saline Vertisols.

1.3.3.6 Saline Micaceous Deltaic Alluvium of Humid Region

The deep micaceous and fine-textured soils of the Ganges delta under humid subtropical climate region are saline to varying magnitudes, with a continuous shallow saline water table. These soils contain neutral salts, which owe their cause to saline substratum and saline water inundations during the time of marine cycles and also in the time of the origin of delta. These soils comprise (a) an ochric epipedon, (b) yellowish brown mottles, (c) uniformly fine texture ranging from clay loam to clay or silty clay and (d) neutral to slightly acid pH. These soils contain the maximum salt deposition in the surface horizon and show predominance of chlorides and sulphates of sodium, calcium and magnesium with small content of bicarbonates, but $CaCO_3$ is not present. The horizon lying immediately beneath the plough layer in these soils consistently becomes very hard due to deposition of silica and operation of frequent rice cropping (Sharma 1995). Characteristics of a typical soil profile are given in Table 1.6.

1.3.3.7 Saline-humic and Acid Sulphate Soils of Humid Tropical Regions

These saline soils are humus-rich and exist in marshy situations along the Malabar Coast. These undergo fresh water submergence from the month of May to December and seawater inundation in tidal cycles for the duration of following lean months. These soils possibly developed under the influence of marine cycle. The salient characteristics of these soils are (a) ochric epipedon; (b) humic horizon in the substratum of some soils; (c) a variety of soil matrix colours varying from pale yellow to very dark grey, greyish brown and dark yellowish brown; (d) signs of gleying, reduction and bleaching in the soil matrix; (d) high EC throughout the profile; (e) soil pH in the acidic range; and (f) high to very high contents of organic matter and a shallow saline water table (Sharma 1998). Occurrence of pyritous clay on Malabar Coast and the variations in soil pH from 3.5 to 7.5 can be attributed to uneven distribution of pyritous clays in the alluvium (Wadia 1966). Characteristics of a typical soil profile are presented in Table 1.7.

1.3.3.8 Saline Marsh of Rann of Kutchh

The great Rann of Kutchh comprises the extensive saline marshy area and has a variety of saline soil types. The process of accumulation is persisting, and textural stratifications are intermixed with bands of gypsum, calcium carbonate and hydrated iron oxide deposition and thus make easy the classification of separate taxonomic units.

A distinct, regular and thick zone of $CaCO_3$ accumulation, mostly dolomitic (Sharma and Bhargava 1981), exists around 1 metre depth from the surface in alkali soils. Sehgal and Stoops (1972) documented that the smooth boundary of the calcic horizon, irregular shape of individual concretion and regularity of existence beneath vast areas draw attention to their pedogenic origin. The zone of calcic horizon probably points out to the zone of shallow water table fluctuation, while recession of water table tends to concentrate the soil solution, and the calcium and magnesium come first to precipitate irreversibly as carbonates. With repetitive hydrological cycles, the precipitates persist to grow in size and occlude the various kinds of soil material (Sharma 1998; Sharma and Bhargava 1981).

Table 1.6 Saline deltaic soil from Sundarbans in 24 Parganas district (West Bengal)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CO_3^{2-} + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	Na^+ (me L^{-1})	Ca^{2+}+Mg^{2+} (me L^{-1})	Clay (%)	$CaCO_3$ (%)
0–12	7.2	27.4	30	0.8	313.4	16.5	156.4	139.1	34.0	Nil
12–80	7.5	7.6	14	1.0	65.5	8.6	40.9	30.4	45.2	do
80–105	6.7	7.5	16	1.2	74.5	9.6	48.5	31.7	46.4	do
105–162	6.4	9.2	21	0.6	98.4	8.3	71.7	44.8	39.3	do
162–184	6.9	10.4	21	0.5	96.2	11.4	74.7	46.1	44.7	do

Source: Bandyopadhyay et al. (1988)

Table 1.7 Saline, acid sulphate soils from Arikum in Calicut district (Kerala)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CEC (me 100 g^{-1})	Ex. H (me L^{-1})	Ca^{2+}+Mg^{2+} (me L^{-1})	Na^+ (me L^{-1})	Cl^{-1} (me L^{-1})	SO_4^{2-} (me L^{-1})	Clay (%)	O.M. (%)
0–9	4.4	43.6	6.4	18.7	2.2	123	322	354	120	47.6	4.8
9–20	4.8	12.6	5.8	20.4	1.2	38	100	105	36	38.8	3.6
20–36	4.8	11.7	6.8	14.7	1.2	44	82	86	53	46.0	2.4
36–70	4.5	8.4	11.1	26.1	1.2	25	76	57	65	63.4	2.6
70+	3.4	38.6	20.5	69.2	18.7	112	285	337	75	50.2	40.5

Source: Bandyopadhyay et al. (1988)

1.3.3.9 Other Categories of Alkali Soils

1.3.3.9.1 Indo-Gangetic Plains

Some other groups of alkali soils which are slightly different from those mentioned above do occur in various parts of the country. These soils may infrequently have a calcic horizon within 50 cm depth from the soil surface. The existence of a shallow calcic horizon is due to either shifting of the surface soil by extreme erosion or deposition of dolomitic material at lower depths because of insufficient leaching. The major characteristics, limitations and ameliorative measures of these soils are comparable to those soils which have a calcic horizon at 1 m or more depth. A shallow calcic horizon has decreased depth of soil for root proliferation and low ability to reserve nutrient and water. Alkali soil with a saline groundwater also occurred in narrow bands in Punjab, Haryana and Uttar Pradesh in regions having 500–700 mm annual rainfall. Shallow saline or alkali groundwater when increased to within 1 m depth triggers the existing sodic conditions (Sharma 1998).

1.3.3.9.2 Black Alkali Soils of Deccan Plateau

The colours of soil matrix vary from grey to very dark grey, dark to very dark greyish brown in the surface horizons and black to dark grey and dark greyish brown in the subsurface horizon. Generally, clay or clay loam soil texture is found, with major parts of subangular blocky structure. These soils have narrow range of workable moisture due to higher stickiness, plasticity and cohesiveness and thus upon drying become very hard and make tillage operation impossible. Moreover, very slow permeability and infiltration is another serious problem in alkali Vertisols. Black soils (Vertisols) also develop deep cracks on drying, because of high coefficient of swelling and shrinkage due to montmorillonitic clays. Smectite particles become deflocculated faster under high degree of sodium saturation and high pH, consequently disintegration of soil aggregates and sealing of pore space take place. Under a buildup of shallow water table environment, high capillary conductivity makes possible rising of water to the soil surface, rendering it extremely moist, saline and unworkable. High pH unfavourably affects solubility and bioavailability of cationic micronutrients, causing severe nutritional disorders. Deficiency of phosphorus is unlikely, because of enhanced solubility of sodium phosphate. Contrary to alkali soils of the Indo-Gangetic alluvial plains, pH and salinity of these soils differ, irregularly and indicative of different phases of alkalization and salinization. These variations are linked with rising water table. The degree of problem becomes more severe, when surface horizons comprise a higher value of pH and high content of salt rather than when these situations exist in subsurface horizons (Bhattacharyya et al. 1994; Sharma 1998).

With regard to alkali Vertisols, the hydraulic properties of soils rely upon the clay mineralogy, ESP of the soil and the concentration and nature of electrolytes in soil solution. The Vertisols of Western India having ESP of approximately 15 comprise extremely poor soil physical properties which makes tillage operations very difficult (Bhattacharyya et al. 1994). Some worker recommended a significantly lower ESP (6) for rating soils to be alkali soils particularly those with a plenty of fine clay and be deficient in soluble weatherable minerals (Northcote and Skene 1972; Shanmuganathan and Oades 1983). Balpande et al. (1996) also recommended an ESP limit of 5 for alkali subgroup of Vertisols in Central India which have high amount of smectite clay mineral (491 g kg^{-1}) in the soil control section. Smectites are considered as high-swelling clays, particularly when Na-saturated (Low 1980). These consist high percentage of clay, exchangeable sodium and cation-exchange capacity. Sodium is mostly dominant throughout the soil depth, but bicarbonate dominates in the deeper layers. Soil salinity and soil pH rise with soil depth. Calcium carbonate exists throughout the soil profile (Sharma 1998). Characteristics of some typical soil profiles are shown in Tables 1.8 and 1.9.

1.4 Historical Perspectives of Management of Salt-affected Soils

In different salt-affected areas of the world, under different natural and economic conditions, countless approaches and methods exist for the utilization and reclamation of these soils. To give the details of these approaches is not the scope of this chapter (many aspects are dealt in different chapters of this book). However, we require different approaches for reclamation and management of alkali and saline soils. Alkali soils are reclaimed mainly by application of amendments such as gypsum, phosphor-gypsum, pyrites, etc. to lower down the pH, while in saline soils the salts are removed from the site through proper drainage (see Szabolcs 1989; Minhas and Tyagi 1998; Dagar 2014; Dagar and Minhas 2016). In both cases biological approaches are also effective. In this chapter some historical perspectives are mentioned in adopting the reclamation approaches.

The earliest research studies conducted on reclamation/bioremediation of alkali soils include series of experiments by Kelley and his associates in California in the 1920s and 1930s (Kelley and Brown 1934; Kelley 1937, 1941, 1951; Kelley et al. 1940). The soil (Natric Durixeralf) of experimental site was fine sandy loam solonetz located on the Kearney Ranch near Fresno having chemical properties in upper 30 cm layer: pH 9.2–9.7, $EC_{1:5}$ 6.1–7.2 dS m^{-1}, CEC 43–44 $mmol_c$ kg^{-1} and ESP 57–70. The soil was uniform in texture to a depth of 60–90 cm, below which there was a compact calcic (mainly $CaCO_3$) layer of 5–15 cm thick. In first phase (in 1920–1921), 37 Mg ha^{-1} gypsum was applied as amendment in two splits (22 kg in 1920 and 15 kg ha^{-1} in 1921). The gypsum application was followed by flooding with well water (EC 0.3 dS m^{-1}, SAR 0.7) and submerged for 3 weeks. The same amount of well water was applied to the bioremediation treatments with adoption of barley (*Hordeum vulgare*) cultivation for 2 years followed by green manuring by Indian sweet clover (*Melilotus indicus*) and white sweet clover (*Melilotus alba*) and a 5-year cultivation of alfalfa (*Medicago sativa*). After alfalfa, the plots were kept fallow for 1 year and then cultivated with cotton (*Gossypium hirsutum*) as first post-reclamation crop. The cotton yields were 1.82 and 2.10 Mg ha^{-1} for gypsum and bioremediation treatments, respectively. Exchangeable sodium percentage of upper 30 cm soil decreased from 70 to 5 in gypsum-treated soil and from 65 to 6 in

Table 1.8 Physico-chemical characteristics of typical alkali soils

Depth (cm)	ECe (dS m^{-1})	pHs	ESP	Ionic composition (me L^{-1})						Particle size analysis (%)			$CaCO_3$ (%)	CEC (me 100 g^{-1})
				Ca^{2+}	Mg^{2+}	Na^+	CO_3^{2-}	HCO_3^-	Cl^-	Sand	Silt	Clay		
(a) Alluvial soil region (Etah, Uttar Pradesh)														
0–16	13.84	10.2	88	0.6	1.6	210	151	28	14	62.0	24.0	14.0	1.9	6.7
16–27	12.50	10.1	87	1.1	1.4	190	129	20	14	57.0	25.5	17.5	4.0	7.3
27–64	4.60	9.7	67	0.5	0.8	45	32	10	11	45.0	22.0	33.0	3.8	15.9
64–81	1.92	9.8	78	1.0	1.5	19	4	13	5	38.0	35.0	27.0	2.7	13.9
81–108	1.88	9.4	24	0.5	1.5	16	4	9	6	34.0	34.0	32.0	12.0	12.9
108–127	2.35	9.1	31	0.5	0.5	21	7	10	6	39.5	33.0	27.5	23.8	12.0
127–148	1.40	8.6	22	1.3	1.4	13	2	6	6	65.0	18.0	17.0	25.0	8.0
(b) Vertisol (Shajapur, Madhya Pradesh)														
0–13	3.5	8.3	60	5.1	5.1	26	Nil	6.3	23.0	15.5	50.0	34.5	8.0	12.0
13–31	1.7	8.4	65	4.2	1.0	8	Nil	9.2	9.0	30.0	45.5	29.5	7.0	12.8
31–62	2.8	8.2	73	2.1	4.8	14	Nil	14.2	8.8	3.0	56.0	42.0	12.8	27.0
62–94	1.6	9.4	51	2.2	4.9	8	Nil	10.2	8.1	4.0	52.5	43.5	21.2	19.0
94–126	6.5	9.1	51	6.1	8.8	59	Nil	87.0	21.0	7.0	46.0	47.4	21.4	25.0
126–158	2.5	8.7	56	2.9	5.1	18	Nil	8.8	10.8	3.0	54.0	48.0	18.7	17.7

Source: Sharma (1998)

Table 1.9 Physico-chemical properties of soils at Panipat district (Nain farm) of Haryana

Depth (cm)	pHs	ECe dS m^{-1}	Na^+ (me L^{-1})	K^+ (me L^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OC (%)	ESP (%)	$CaCO_3$ (%)	CEC cmol kg^{-1}	Sand (%)	Silt (%)	Clay (%)
Pedon 1: 29°19′04.1″N and 76°47′55.1″E, coarse loamy, mixed sodic Haplustepts, grasses, *Prosopis juliflora* grown, water table depth <2.5 m															
0–16	9.0	58	1217	5.7	10	2.0	500	71.9	0.45	30.9	2.1	10.6	81.4	13.0	5.5
16–42	9.4	31	659	0.6	7	1.5	240	69.5	0.30	43.9	1.4	8.0	57.5	25.1	17.4
42–77	9.5	13	243	0.01	5	1.5	95	56.3	0.27	44.0	1.3	14.5	58.3	20.7	20.9
77–112	9.6	10	183	0.1	5	2.0	75	20.9	0.18	54.0	1.9	13.0	63.8	18.8	17.3
112–150	9.7	10	207	0.1	5	2.0	69	19.2	0.22	55.3	10.1	11.5	59.2	25.2	15.5
150–180	9.6	11	234	0.1	5	2.0	77	25.8	0.19	58.0	13.2	20.4	39.9	34.9	25.1
180–220	9.5	15	301	0.1	5	2.0	92	30.5	0.24	55.0	15.1	22.8	48.8	27.6	23.5
Pedon 2: 29°19′02.9″N and 76°47′50.3″E, fine loamy, mixed Typic Haplustepts (saline phase), *Prosopis juliflora* grown, water table depth <3.5 m															
0–23	8.5	71	1908	1.0	48	0	500	71.8	0.34	25.0	1.2	13.6	68.6	18.9	12.3
23–73	8.2	45	1241	0.5	45	1.5	240	71.1	0.31	20.0	1.3	13.9	58.6	21.8	19.5
73–110	8.4	20	406	02	17	1.5	95	68.6	0.22	29.0	1.6	19.7	54.8	20.1	25.1
110–145	8.5	21	273	02	20	2.0	75	66.4	0.28	21.2	2.1	12.1	54.1	24.3	21.6
145–170	8.1	23	469	01	41	2.0	69	64.5	0.22	29.5	8.8	16.6	70.0	16.2	13.8
170–192	8.7	25	469	0.1	63	2.0	77	59.9	0.24	33.3	9.0	19.7	55.8	25.7	18.4
192–252	8.7	19	336	0.1	55	2.0	91	64.3	0.25	37.5	10.2	14.7	48.0	35.4	16.5
Pedon 3: 29°19′04.5″N and 76°47′42.4″E, coarse loamy, mixed Sodic Haplustepts, partly barren, grasses grown, water table depth >5 m															
0–20	10.0	82	2577	3.0	5	5.5	775	126.5	0.25	77.1	2.52	9.8	68.5	20.5	10.9
20–60	9.5	28	505	0.4	6	1	210	69.5	0.27	68.8	1.05	11.4	59.5	23.2	17.2
60–85	9.0	14	257	0.1	17	0.5	87	56.3	0.24	50.0	1.89	10.4	58.3	20.8	20.8
85–132	8.9	13	248	0.1	19	0.5	75	54.5	0.24	57.0	6.51	11.7	59.1	23.5	17.2
132–158	9.0	19	414	0.2	29	1.5	118	53.0	0.25	60.4	7.77	12.1	55.4	29.7	14.8
158–175	9.0	21	381	0.1	32	1	130	69.9	0.24	56.4	12.82	7.3	40.6	43.2	16.0
175–229	8.9	17	269	0.2	33	1	97	64.7	0.24	45.9	16.17	9.8	34.1	47.2	18.5

Pedon 4: 29°19′08.4″N and 76°47′34.8″E, coarse loamy, mixed Typic Haplustepts, grasses and *Prosopis juliflora* grown, water table depth >5 m															
0–22	7.7	14.1	174	1.0	49	3	86	64.1	0.49	16.4	1.1	12.2	62.0	21.2	16.7
22–53	8.0	21.3	273	0.8	51	2	134	65.6	0.28	19.9	0.2	7.5	65.1	19.9	14.8
53–85	8.0	25.3	321	0.9	50	1.5	166	68.9	0.18	34.9	0.2	6.7	60.5	19.7	19.7
85–117	8.2	25.4	326	0.8	60	2	176	67.4	0.18	40.9	1.1	5.74	57.1	30.8	11.9
117–160	8.4	21.3	274	0.7	52	1	140	68.1	0.18	23.8	6.1	8.00	57.1	26.2	16.6

Source: Mandal et al. (2013)

bioremediation plots. In the second phase (1930–1937), also under bioremediation [with Bermuda grass (*Cynodon dactylon*) for 2 years followed by barley for 1 year, alfala for 4 years and oats (*Avena sativa*) for 1 year], the ESP values of upper 30 cm soil reduced from 57 to just 1 after 8 years (Kelley 1937; cited by Qadir and Oster 2002). Similar bioremediation results were also obtained in irrigated meadow experiments at Bekescsaba, Hungary (de Sigmond 1923, 1924, 1927), and at Vale, Oregon (Wursten and Powers 1934). The last major reclamation effort in California was along the west side of the San Joaquin Valley brought under irrigation during the 1950s and 1960s. Cropping during reclamation was a common practice, and chemical amendments such as gypsum, sulphur and sulphuric acid were used selectively (Kelley 1941, 1951). Barley, a winter crop, was usually the first crop during reclamation followed by cotton and other crops.

Alberta Agriculture (1979) reported that the extent and severity of saline seeps are increasing in Western Canada and the North Great Plains at a rate of 5% per year. In Montana, the rate of increase in salt-affected areas was also found to vary from year to year depending on the climate. An Albertan survey on the Peigan Indian Reserve showed a threefold increase in saline seep acreage on cultivated land over a period of 10 years from 1961 to 1970 (Vander Pluym 1978). Cannon and Wentz (2000) used the historical data of over a 55-year period covering large areas in aerial photography and found the technique most reliable in central and southern Alberta. A series of air photos were used by them to determine the extent of visible salinity for each decade since 1950 for 89 sites in the brown, dark brown and black soil zones in Alberta. Total visible salinity for all sites fluctuated considerably over the monitored 50-year period. The results were similar to Harker et al. (1996) who monitored 55-year data for southern Alberta.

The farming history of salt-affected soils of the Indian subcontinent reveals that most farmers typically began reclamation during the high rainfall months (July to September) resulting in considerable leaching and reclamation. Singh (1998a) tried to connect the entire historical account of reclamation which has been briefed here. In the Indian subcontinent, as early as 1879, a *Reh* (salinity) Committee was constituted to deliberate on the origin of salts in soils. HB Medlicott, Director, Geological Survey, and a major contributor member of the committee, elaborated on two important sources of salts in soils, i.e. weathering of soil constituents and role of canal water irrigation. As per his statement, ‘*Reh* is formed of highly soluble sodium salts resulting from decomposition of the rock minerals by air and water’. Being the waste product of soil formation, *Reh* itself generally occurs in soils due to ‘elements unassimilated by vegetation and their gradual removal as a consequence of the rain water draining through the soil and carrying with it any excess of these highly soluble salts’. On the contribution of canal water, Medlicott emphasized that it was a perpetual independent and an inexhaustible source of salts. Sir EC Buck, in his note to the *Reh* Committee, described the role of wind in picking and depositing salts. Similarly, FN Wright also suggested the role of winds blowing over places covered with salt efflorescence and salt deposition in the adjoining fields in hot months. Wright further noted the rise in water level in the vicinity of the canal and thus reaffirmed the assertion of Medlicott on the role of canals in soil salinization.

Though *Reh* committee discussions did not lead to any conclusion on the theory of alkali formation in soils, the views of Medlicott seem to have prevailed. Another outcome was that a scheme of experimental work was drawn up, to be carried out mainly by the newly formed agricultural department (Singh 1998a).

1.4.1 *Reh* Committee Recommendations and Their Follow-up (Singh 1998a)

The *Reh* Committee recommendations were mainly directed towards preparing the soil for profitable cultivation adopting practices for removal of salts, proper drainage, avoiding silting, deep cultivation, adequate manuring and ploughing of green crops. To decide the course of action for the reclamation of salt lands, a conference was held in 1879 at Aligarh. The main decisions of the conference, as documented by Leather (1897), were the following:

- Prepare *Reh* maps to ascertain *Reh* distribution throughout the provinces, and study its variations over the years in certain selected villages. Accordingly, the maps were prepared, and a series of observations were made in 65 villages of Akbrabad pargana in Aligarh district.
- A survey of subsoil waters showing depth to water table was done, and a surface drainage map was also prepared for the same villages of Akbrabad. A number of agricultural experiments were started at Awagarh, Aligarh and Kanpur.
- The effect of surface drainage was tested by erecting small embankments and allowing rainwater to leach them. According to Leather, the experiment appeared to have been a failure. Likewise, 2-inch pipes were laid in another plot, but the pipes silted up, making the experiment fruitless. Similarly scraping the *reh* off the surface also proved quite useless.
- Near Aligarh, another experiment on reclamation of *usar* was started with land enclosure and planting of trees. Plantations were also grown at other locations in Aligarh and Kanpur districts. Variable success was observed with use of manure along with initial leaching through embankments of plantations and grassland. Crops like barley and peas in *rabi* and at some places rice in rainy season (*kharif*) were cultivated in these experiments. The lands showing improvement were later leased.

Greig (1883), after visiting one plantation at Purdilnagar near Sikandra Rao in the Aligarh district and seven plantations near Awagarh, made some important observations on the heterogeneity in salt lands. He recorded that a simple and reliable way of finding good patches in a *usar* plot was to stop grazing for a year and then examine the ground. *Dub* (*Cynodon dactylon*) and other grasses appeared on good patches, but only one kind of grass that was not found on any other soils grew on highly *reh*-impregnated soil (may be *Desmostachya bipinnata*). According to him in real *usar*, the trees only did well if the pits filled with good soil were deep enough to let the roots extend beyond 90 to 120 cm of *reh* into a less deteriorated soil below. These observations formed the basis of the auger-hole method of planting trees in alkali soils later advocated by the Central Soil Salinity Research Institute, Karnal.

JA Voelker, in 1891, observed that the results of the experiments were not supported by analysis of experimental site soil and thus it was difficult to make an accurate opinion about their application to other *usar*-affected lands (cited by Moreland 1901). For better understanding of these investigations, JW Leather was included as agricultural chemist in the staff of the Imperial Department. Consequently, after thorough investigations of reports of experimental farms at Amarmau and Juhi in Kanpur district and Chherat and Gursikran in Aligarh district, Leather (1893) described causes of accumulation of salts, the effects of canals and details of reclamation methods followed by the farmers and the experiments carried out under the scheme of *Reh* Committee.

1.4.2 Reclamation Experiments (Mostly Based on Reported by Singh 1998a)

1.4.2.1 Sind Area

The *usar* reclamation was first commenced at Mirpur Khas, Daulatpur and Sukkur on two major soil types, i.e. the clayey soils near river Indus and its old branches and the coarse-textured soils. Henderson (1909) observed that no crops were growing on a part of Mirpur Khas farm because of varied presence of the salt content (0.08–0.98%) with dominance of sulphates in different plots. Continuous ponding of 5 cm water for 4 to 5 months followed by sowing of Egyptian clover, cotton, pearl millet and Sindhi cotton in different years helped in reclamation of salty soils at Sukkur and Mirpur Khas (Henderson 1909). The work was started in bad *kallar* site with chloride-dominant salt content ranging from 0.1% to 1.54% at Daulatpur in the beginning of 1908. The land was levelled and drained to wash down the salts into subsoil and repeated growing of Egyptian clover (Henderson 1914). Sind experiments suggested importance of Egyptian clover and rice in reclamation of all hues of salt-affected soils in Sind and Punjab.

Commissioning of Sukkur Barrage, in highly salt-impregnated finer texture soil with brackish groundwater and poor drainage areas in Sindh, was supposed to create large-scale irrigation potential and consequent simultaneous new problems as experienced elsewhere. To better understand the processes responsible for soil degradation and its productive use in advance, a committee presided over by the Commissioner of Sind in Karachi early in 1924 recommended the establishment of a first-class agricultural research station at Sakrand in a typical canal-irrigated area (Mann 1927). The Sakrand experiments were planned mainly to answer the questions like development of soil salinity, possible loss in soil fertility, danger of waterlogging, etc.

1.4.2.2 Punjab

Though the first official notice of soil salinity in canal commands of India came from the eastern part of the then Punjab, it was the western part that faced the real threat, so much so that the land allottees in Rangpur and Mailsi canal commands abandoned their lands because of the 'white devil'. The standard practice of growing rice-Egyptian clover rotation for reclamation did not succeed everywhere, and some soils of Sindh needed gypsum application for their reclamation (Henderson 1914). This kind of land treatment was more important in so-called *bara/bari* soils first encountered in the Bari Doab of Punjab, the area between Beas and Ravi rivers. The distinction between saline and alkali soils for the purpose of treatment was made only on the basis of their physical traits like hardness and permeability to water. Analysis of soils formed the basis of diagnostics tool for distinction of salinity and alkalinity only after joining of Mr. JH Barnes as first agricultural chemist to the Punjab government in 1906. The importance of the scientific investigations on *reh* can be judged from excerpts of regrets for noncompletion of the chemical laboratory at Lyallpur in the 1909 report of the Joint Secretary to the Financial Commissioner, Punjab. The Joint Secretary further hoped that the agricultural chemist would be able to make some headway with his necessary preliminary investigations in the following year. An important step of formation of a small committee was taken at the 1909 agricultural conference of Nagpur. This committee was entrusted the task to ensure the proper coordination of the work on *reh*, which is being undertaken in most of the Provinces in India, and the consequent acceleration of practical results from through scientific investigations.

At the instance of Barnes, the Punjab government in 1908 surveyed the Lower Chenab command area to investigate the extent of salt problem. Waterlogging had been noticed in the new canal commands of Punjab which also caused soil salinity. Mr. Barnes initiated reclamation experiment at Narwala in 1915. His studies on deep cultivation, drainage and salt washing successfully reclaimed soil which was restored to original owners. He proposed a similar alkali reclamation scheme for the Lower Bari Doab command just before his unfortunate demise (Mackenna 1918). Nevertheless, the Punjab government was so impressed by the success of Narwala reclamation work that a scheme was sanctioned to reclaim crown lands in Lower Bari Doab Canal commands on a 663 ha area with various levels of deterioration. Simultaneously, pot experiments were laid on *bara* soil at Pusa. Barnes and Ali (1917) and later Nasir (1923) used gypsum to study the increase in ammonification activity of soil micro-organisms in alkali soils. Use of gypsum with the clear objective of replacing exchangeable sodium of the soil by calcium in amendment started only when the scientists clearly understood the phenomenon of cation exchange. Comparison of calcium chloride and gypsum for this purpose by Singh and Nijhawan (1932) and Puri (1934) was a landmark research effort in this direction.

1.4.2.3 Black Soil Region

Based on the Nira Valley Expert Committee (1903) recommendations and November 1905 resolution of the Revenue Department, experiments on amelioration of salt lands of the Nira Valley were initiated under the supervision of Mr. Knight in 1908. Mann and Tamhane visited these experiments in 1909; examined water samples from river, canal and the holes dug in the soil; and concluded that salty subsoil water within 1.5 m depth existed throughout a large part of Nira canal area (Mann and Tamhane 1910). They cautioned that a slight error on the part of the cultivators could bring these salts to the surface and ruin the land. They concluded that salt land in the Nira canal command was due solely to the raising of the water level as a consequence of the existence of the canal in the area. The area under barren lands was increasing in almost all canal-irrigated areas with accumulation of salt in variable degrees, and as regards control measures, it was suggested that deepening of main drainage channels, chiefly *nalas*, could prevent extension of the problem. The restriction of water would lower the subsoil water level, and withdrawal of water from the area could lead to gradual recovery, especially where salt buildup had just begun. They proposed that digging at least 75 cm deep drains across the line of natural drainage of the land with an adequate outlet and then thorough salt washing by frequent irrigations after bunding the land was only successful method of recovery of barren lands. However, in his comments on the bulletin by Mann and Tamhane, Leather (1911) asserted that no system of drains that ran only across the lines of natural drainage could possibly be effective either in the Deccan or elsewhere. In fact, he gave considerable value to reclamation work comprising minor drains, running across the direction of natural flow, and a major drain, running in the direction of natural flow into which the minors emptied.

To manage the problem of waterlogging and salt buildup, noticed in the tank-irrigated areas of southern India, a number of experiments on stone and tile drains were initiated at Saidapet in Madras Presidency by Robertson in 1873. His observation of silting of drains despite using collars warranted more research to sort out the problem. Wood (1914) reported work on subsoil drainage to reduce soil salinity of rice lands under tank irrigation of the central farm, Coimbatore. His experiments included two kinds of drains, i.e. plain loose stones and tar dipped end-to-end threaded long bamboo tubes laid in 1910 and worked up to 1914. In other experiments stone drains laid in 'alkaline' rice land had been running for 5 years and making the land fertile. Wood (1914) considered these experiments a financial success.

1.4.3 Post-independence Reclamation

1.4.3.1 Sharda Sahayak Canal Command Area

Sharda Sahayak Canal, commissioned in 1978 to provide irrigation to 1.67 million ha area in 21 districts of Uttar Pradesh in northeast India, markedly increased agriculture productivity in the command area. However, absence of drainage and continuous seepage from the canal resulted in a rise in water table and subsequent upward flux of salts to the surface soil layers inflicting salinity in ~ 0.37 million ha area in a span of three decades. Out of this, nearly 0.15 million ha area has been estimated as sodic (higher concentration of sodium carbonate and sodium bicarbonate in the profile) with shallow water table. The present scenario is that more than 1 km area adjacent to both sides of the canal has gone out of cultivation and the farmers have almost abandoned their lands. In extreme cases, mango plantations of more than 20 years old started withering and drying (Singh 2009).

1.4.3.2 Indira Gandhi Nahar Project (IGNP)

IGNP earlier known as Rajasthan canal project was launched to provide drinking and irrigation facilities to 1.79 million ha area in the districts of Ganganagar, Hanumangarh, Bikaner, Jaiselmer, Jodhpur, Barmer and Churu in the arid north-west tract of Rajasthan. The IGNP command area receives an annual rainfall of 30 cm in feeder canal area to less than 12 cm in Jaiselmer area, while the potential evaporation varies from 160 to 200 cm per annum. As such the soils of the region can be divided into the floodplain soils (54% of the area) and aeolian soils (46% of the area). The floodplain soils are mainly fine sandy, deep calcareous, highly stratified loams with good water-holding capacity, with roughly 10% being saline or moderately alkaline. The aeolian soils, in general, are coarse textured, deep and calcareous with low fertility and are highly susceptible to wind erosion. Soils in Jamsar, Lunkaransar, Soorsar, Dattor, Sallor distributory and Khusar minor and Mohangarh are gypsiferous. The gypsiferous soils are in general shallow and found in intra-dunes flats at low-lying areas. Due to the presence of a hard and impervious layer, its management is difficult. The introduction of irrigation in desert area brought about a mini green revolution and considerable prosperity to the farmers. Some of the positive impacts of the introduction of irrigation in the desert included improvement in microclimate, change in land use and in cropping pattern and improvement of soil and moisture conditions and associated biological activities in the soils. However, few years after the introduction of irrigation, several negative effects such as rise in the water table, waterlogging, formation of marshy lands, increased soil salinity and decreased biodiversity also emerged. The current estimates indicate that about 0.18 million ha land is already affected by salinity and sodicity in IGNP command. The salt-affected soils in this command are mainly located in Anupgarh branch, Suratgarh branch and Eastern block. Because of poor infiltration rate, high bulk density, poorly developed structure, stratification and hard crust formation in the soil, the maximum area under salinity/sodicity is in Anupgarh branch. The soils are predominately clay to silty clay with blocky structure and are thus difficult to cultivate when dry and remain wet for a longer time than normal soils. Electrical conductivity in these soils varies from 0.50 to 55.0 dS m^{-1} and pH from 8.5 to 9.0. It has been observed that on both the north and south sides of Rajasthan Canal Feeder (Badopal, Dabli, Seelwala and Tibi areas), the depth of water table is <2 m. Between Rawatsar and Masitawali head, the problem is mainly due to seepage of canal water, whereas in Lunkaransar lift canal area, the problem is of perched water table. Similarly, in part of Ghaggar floodplain area, the problem has developed due to water stagnation in the depressions. Groundwater is saline in large part of IGNP with EC varying between 0.4 and 39.6 dS m^{-1}. However, presence of a cushion of good-quality water in the Ghaggar plain and low EC (3.0 dS m^{-1}) in the vicinity of canals, indicating fresh water quality zone is developing gradually and floating over the poor-quality groundwater, and has tremendous scope for irrigation. Since there is no natural drainage system, more and more areas are getting waterlogged and salinized resulting in desertification. A sizable area has already gone out of cultivation, and several villages have been abandoned. In some of the extreme cases, people feel that they were better when the irrigation was not introduced in the desert area (Singh 2009).

1.5 Saline Aquaculture-induced Soil and Water Degradation in Coastal Belt

Owing to high remuneration from aquaculture, many rice fields are being converted to brackish water aqua farms during last decade in coastal areas of Andhra Pradesh. Within 10 km of the seacoast, farmers draw and store millions of gallons of salt-laden brackish (35–40 dS m^{-1}) seawater into big aquaculture (prawns) tanks and blended with canal or groundwater to lower salinity to 18–20 dS m^{-1} on nearly 2 lakh ha land of Andhra Pradesh. Due to fatal viral contamination of the prawn ponds, when farmers revert back to rice cultivation, they are unable to grow a successful crop because of severe salinity in the pond soils.

1.6 ICAR Research on Reclamation

In the past, research was conducted by individual scientist or group of scientists of the state departments of agriculture and irrigation, state agriculture colleges and universities and the Imperial Agricultural Research Institute without much technical or material support from the central government. To overcome the food shortages in the country, India embarked on a 5-year development plan, with strong emphasis on agricultural development. The Indian Council of Agricultural Research (ICAR) financed agriculture research schemes to the state departments of agriculture and a country-wide research network with good research infrastructure, and trained manpower was added with the establishment of state agricultural universities during the period of third plan and later. During this period the ICAR started All India Coordinated Research Projects (AICRP), with centres in different state agricultural universities (SAUs) and even in private institutions and colleges located in different agroecological zones of the country. Thus, research on the reclamation of salt-affected soils was mainly carried out under the auspices of the ICAR through:

1. ICAR-sponsored research schemes during the second 5-year plan and ad hoc research schemes
2. All India Coordinated Research Project on Water Management and Soil Salinity (now All India Coordinated Research Project for Management of Salt-affected Soils and Use of Saline Water in Agriculture)
3. The Central Soil Salinity Research Institute, Karnal, set up in 1969

Besides the ICAR projects, alkali soil reclamation research was also carried out by the National Botanical Research Institute, Lucknow, at its farm at Banthra, by individual scientists and postgraduate students in state agricultural universities, traditional universities, research institutes and the state department of agriculture. During the second 5-year plan, the ICAR research projects on land reclamation were located at Ludhiana and Allahabad. The Ludhiana centre carried out research on comparative performance of different chemical amendments like gypsum, press-mud, commercial acids, aluminium sulphate and ferrous sulphate and organic amendments like molasses, farm manure, different kinds of plant residues and *Sesbania* green manure, different crop rotations, deep tillage and nutrient use at Kamma and Nilokheri research stations in Ludhiana and Karnal districts, respectively. The research results of Ludhiana centre were later extended to the field through an Operational Research Project situated in district of Kapurthala and through field demonstrations elsewhere in Punjab. The Allahabad centre conducted research on assessment and use of organic amendments in alkali soil reclamation.

The All India Coordinated Project for Research on Use of Saline Water in Agriculture was first sanctioned during the Fourth Five Year Plan under the aegis of Indian Council of Agricultural Research, New Delhi, at four research centres, namely, Agra, Bapatla, Dharwad and Nagpur. The project undertakes research on saline water use for semiarid areas with light-textured soils, arid areas of black soils region and coastal areas and on the utilization of sewage water, respectively. During the Fifth Five Year Plan, the work of the project continued at the above four centres. In the Sixth Five Year Plan, four centres, namely, Kanpur, Indore, Jobner and Pali, earlier associated with AICRP on Water Management and Soil Salinity were also transferred to this Project, whereas the Nagpur Centre was dissociated. As the mandate of the Kanpur and Indore centres included reclamation and management of heavy-textured alkali soils of alluvial and black soil regions, the Project was redesignated as All India Coordinated Research Project on Management of Salt Affected Soils and Use of Saline Water in Agriculture. Two of its centres located at Dharwad and Jobner were shifted to Gangawati (w.e.f. 1.4.1989) and Bikaner (w.e.f. 1.4.1990), respectively, to conduct research right at the large chunks of salt-affected locations. During the Seventh Plan, the project continued at the above locations. During the Eighth Five Year Plan, two new centres at Hisar and Tiruchirappalli were added. These centres started functioning from 1 January 1995 and 1997, respectively (AICRP 2012–2014). Further, with the addition of four new volunteer centres in 2014, currently this AICRP has the following eight cooperating and four volunteer centres:

Cooperating Centres

- Raja Balwant Singh College, Bichpuri, Agra (Uttar Pradesh)
- Regional Research Station, Acharya N.G. Ranga Agricultural University Bapatla (Andhra Pradesh)
- SK Rajasthan Agricultural University, Bikaner (Rajasthan)
- Agricultural Research Station, University of Agricultural Sciences, Gangawati (Karnataka)
- Department of Soils, CCS Haryana Agricultural University, Hisar (Haryana)
- Agriculture College, RVS Krishi Vishwa Vidyalaya, Indore (Madhya Pradesh)
- Agriculture College, CS Azad University of Agriculture & Technology Kanpur (Uttar Pradesh)
- Agriculture College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli (Tamil Nadu)

Volunteer Centres

1. Regional Research Station, Punjab Agricultural University, Bathinda (Punjab)
2. Khar Land Research Station, Panvel (Maharashtra)
3. ICAR-Central Island Agricultural Research Institute, Port Blair (A&N Islands)
4. Rice Research Station, Kerala Agricultural University, Vyttila, Kochi (Kerala)

It is a coincidence that the ICAR-CSSRI is located on the bank of western Jamuna canal along which soil salinity was first reported in 1855 at the village of Munak, about 30 km downstream the bridge near ICAR-CSSRI. The institute focuses the research on the reclamation and sustainable management of salt-affected soils and on the rational use of poor-quality water in agriculture. The institute research programs are implemented through four research divisions: Soil and Crop Management, Crop Improvement, Irrigation and Drainage Engineering and Technology Evaluation and Transfer. Besides the main campus at Zarifa Viran Village, Kachhwa Road, Karnal (Harayana), the institute has three regional research stations at Canning Town (West Bengal), Bharuch (Gujarat) and Lucknow (Uttar Pradesh).

Regional Research Station, Canning Town, West Bengal, was transferred from ICAR-CRRI, Cuttack, to ICAR-CSSRI in 1970. The station conducts research to generate location-specific technologies for the productive use of coastal saline soils. To conduct researches on inland salinity of the black soil (Vertisols) regions of the country, a regional research station was established at Anand in Gujarat in 1989. The research activities were carried out at the research farm in Khanpur. On the recommendations of the QRT (1986–1995), the station was shifted to true Vertisol area in Bharuch in 2002. Third Regional Research Station was established, at Lucknow in Uttar Pradesh in 1999, to deal with the problems of alkali soils of central and eastern parts of Indo-Gangetic Plains having problems like surface drainage congestion, high water table, relatively heavy-textured soils and indurated pan.

ICAR-CSSRI has digitized maps of salt-affected soils on 1:2, 50,000 scales for all 15 states having salt-affected soils. Total salt-affected area in the country has been computed to be 67, 44,968 ha. ICAR-CSSRI has also prepared a first approximation map of groundwater quality on 1:6 million scales. Approximately 32–84% area under arid and semiarid states is covered under saline/sodic groundwater. Chemical amendment (gypsum)-based package of alkali soil reclamation technology for reclamation has been developed, standardized for different types of alkali soils and popularized. It has been handed over to State Land Reclamation Development Corporation for large-scale implementation. Subsurface drainage technology consisting of a network of concrete or PVC pipes covered with gravel or synthetic filter, installed manually or mechanically at design spacing and depth below soil surface, has been developed and standardized for different textural class soils. It has been found very effective in controlling the water table and promoting the salt leaching process. The technology, developed initially for Haryana, has been widely adopted and replicated in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Madhya Pradesh, Maharashtra and Karnataka. As a follow-up of Indo-Dutch project, the institute was associated with Haryana Operational Pilot Project (HOPP), and this collaboration is ongoing for the monitoring of large-scale drainage projects in various districts of the state. The technology in Maharashtra is now being pursued under Public-Private Partnership Limited, Sangli, with funding from the Ministry of Rural Development to the Water Resources Department, Maharashtra (CSSRI – At a glance 2010).

For enhancing crop productivity in salt-affected areas, ICAR-CSSRI has developed eight salt-tolerant varieties of rice (CSR 46 in 2014, CSR 43 in 2011, CSR 36 in 2005, CSR 23 in 2004, CSR 30 in 2001, CSR 13 and CSR 27 in 1998 and CSR 10 in 1989), five salt-tolerant varieties of wheat (KRL 1–4 in 1990, KRL 19 in 2000, KRL 210, KRL 213 in 2010 and KRL 283 in 2018), five salt-tolerant varieties of mustard (CS 52 in 1997, CS 54 in 2005, CS 56 in 2008, CS 58 in 2017 and CS 60 in 2018) and one chickpea variety (Karnal Chana-1) through hybridization breeding approach (ICAR-CSSRI 2018).

ICAR-CSSRI has developed an augur hole technology for raising forest and fruit tree plantation in salt-affected soils for the reclamation of highly deteriorated (mainly community) lands. Several experiments have been conducted at ICAR-CSSRI, Karnal, and elsewhere to study the performance of grasses in association with salt-tolerant trees like *Prosopis juliflora* and *Acacia nilotica* in unified agroforestry systems (Singh et al. 1988; Singh 1995; Dagar et al. 2001; Singh and Dagar 2005). A field study conducted at Gudha Experimental Farm for 6 years indicated that grass *Leptochloa fusca* has the potential to yield about 20 Mg ha^{-1} of green biomass per annum when planted with *Prosopis juliflora* in an alkali soil of pH 10.4. *Leptochloa* grass, identified as a highly sodicity tolerant species, has a special characteristic where it starts disappearing when sodicity level in the soil decreases that allows the regeneration of other moderately salt-tolerant grasses and other annuals. The results of this experiment clearly indicated that sodic soils can be reclaimed by growing *Prosopis juliflora* and *Leptochloa fusca* for 5 years. During this period, the surface soil is reclaimed, and salt-tolerant crops like Egyptian clover (*Trifolium alexandrinum*), oats and Indian clover (*Melilotus* spp.) can be grown without the application of amendments. Likewise, oats, rye grass and Persian clover have also been established as salinity-tolerant fodder crops which can be successfully grown with saline drainage effluents (Yadav et al. 2007). Apart from this ICAR-CSSRI also developed some important technologies of practical importance, i.e. land-shaping technologies, biodrainage, safer disposal of wastewater in high-rate transpiration of *Eucalyptus* plantations (Minhas et al. 2015) and CSR-BIO consortia for enhancing productivity in sodic soils. Recently, the reclamation work carried out in Indian subcontinent has been documented widely in many quality publications (Dagar et al. 2001; Qadir and Oster 2002; Singh and Dagar 2005; Dagar 2014; Dagar and Minhas 2016; Dagar et al. 2016a, b).

Important Institutions Pursuing Reclamation and Management of Salt-affected Soils

- Water and Land Management Institute (WALMI), Anand, Gujarat
- Command Area Development Authority, IGNP, Rajasthan
- Command Area Development Authority, Tungabhadra Project, Karnataka

- Haryana Land Reclamation & Development Corporation (HLRDC), Haryana
- Uttar Pradesh Bhumi Sudhar Nigam (UPBSN), Lucknow
- Punjab Land Reclamation Development Corporation (PLRDC), Chandigarh
- Gujarat Land Reclamation & Development Corporation, Gandhinagar
- National Bank for Agriculture and Rural Development (NABARD) financing land reclamation and soil improvement projects
- Sundarban Development Board (SDB), West Bengal

1.7 Saline and Sodic (Alkali) Waters for Irrigation

1.7.1 Historical Perspectives and Distribution

Through the ages, man inhabited water scarcity regions. In due course, ecological pressures caused by increase in human and animal population forced him to look for irrigation water resources to grow food and fodder crops. With no choice of different-quality waters, particularly in dry ecologies, he often had to use poor-quality groundwaters, available in the terrain, for irrigation. The instinct of survival in harsh environment has made the man to learn the practices for judicious use of this water to avoid the decline in soil fertility due to saline irrigation. For instance, in western Rajasthan, where saline irrigation has been practised since ages, the farmers chose to raise barley or later a high salt-tolerant variety of wheat (Kharchia), and the land was kept fallow during monsoon to leach down the salt developed due to saline irrigation. Thus, farmers learnt the art of saline irrigation and lived along with salinity from time immemorial.

The International Groundwater Resources Centre (IGRAC) has compiled global geographical distribution of saline groundwater to a depth of 500 m. The total area, where groundwater salinity at shallow or intermediate depth is considered, approximates 24 million km^2, which is about 16% of the total land area on earth (van Weert et al. 2009). Globally, 36 groundwater regions have been identified, and Groundwater Region 25 (basins of West and Central Asia) is the largest area with high groundwater salinity contributing 14% to the total saline groundwater area. The Global Groundwater regions 7 (lowlands of South America), 11 (lowlands of Europe), 24 (mountain belt of central and eastern Asia) and 35 (Eastern Australia) contribute individually to about 6–7% of the total saline groundwater area (Table 1.10). Based on this study, though it is not possible to estimate the volume of saline groundwater, as per population data of year 2000, about 1.1 billion people live in areas with groundwater salinity at shallow and intermediate depths.

1.7.2 Genesis of Saline Groundwater

A large part of saline groundwater often comparable to good-quality water is young and tends to be actively recharged. It is more or less in stagnant condition at greater depths and may have been there already for many thousands or even millions of

Table 1.10 Global distribution of saline groundwater in different areas at shallow and intermediate depths

Global groundwater region	Countries included	Main physiographic units/ geological provinces
1: Western mountain belt of North and Central America	Parts of Canada, USA, Mexico, Guatemala, Belize, Honduras, Nicaragua and Costa Rica, all of El Salvador and Panama	(a) Alaska, (b) Cordilleran Orogen of Canada, (c) Pacific Mountain System, (d) Columbia Plateau, (e) Basin and Range, (f) Colorado Plateau, (g) Rocky Mountains System, (h) Central American ranges (including Mexican Sierras)
2: Central plains of North and Central America	Parts of Canada, USA, and Mexico	(a) Interior platform of Canada, (b) interior plains of USA, (c) interior highlands, (d) Sierra Madre Oriental
3: Canadian shield	Greenland, parts of Canada and USA	(a) Seven geological provinces of Canadian shield, (b) Innuitian orogeny, (c) Hudson Bay Lowlands (d) Arctic Platform, (e) St. Lawrence Platform, (f) Laurentian Platform of the USA, (g) Greenland
4: Appalachian highlands	Part of Canada and USA	(a) Appalachian Orogen in Canada, (b) Appalachian Highlands in the USA
5: Caribbean islands and coastal plains of North and Central America	Cuba, Jamaica, Haiti, Dominican Republic, Puerto Rico and Lesser Antilles; parts of the USA, Mexico, Guatemala, Belize, Honduras, Nicaragua and Costa Rica	(a) Atlantic Planes (incl. Florida Peninsula), (b) Mexican Gulf Plains (incl. Yucatan Peninsula), (c) Caribbean Plains, (d) Caribbean islands
6: Andean belt	Almost the total territory of Chile and parts of Venezuela, Colombia, Ecuador, Peru, Bolivia and Argentina	(a) Andes, (b) Altiplano, (c) Coastal
7: Lowlands of South America	Parts of Venezuela, Colombia, Brazil, Ecuador, Peru, Bolivia, Paraguay, Argentina, Uruguay and Chile	(a) Orinoco basin (Northern llanos Basins), (b) Amazon basin, (c) Pantanal and Gran Chaco, (d) Pampas with Rio de la Plata estuary, (e) Parana Basin, (f) Patagonia plains
8: Guyana Shield	Guyana, Suriname, French Guyana and parts of Venezuela, Colombia and Brazil	(a) Guyana Shield province: mainly Precambrian igneous and metamorphic rocks with low potential for storing and transmitting groundwater. (b) Guyana Coastal province: deltaic multilayer sandy aquifer systems in the coastal lowlands. They are the main aquifers of the region

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
9: Brazilian Shield and associated basins	Parts of Brazil and Bolivia	(a) Brazilian Shield (North, Central, East and South), (b) Parnaiba Basin, (c) Sao Francisco Basin, (d) Brazilian coastal
10: Baltic and Celtic shield	Iceland, Norway, Sweden, Finland, Ireland and parts of the UK (N. Ireland, Scotland, Wales), France (Bretagne), Estonia (North) and Russia (Karelia)	(a) Baltic Shield (b) Norwegian Caledonides, (c) Island of Iceland, (d) Ireland-Scotland Platform, (e) Armorican Massif
11: Lowlands of Europe	Denmark, the Netherlands, Belgium, Luxembourg, Lithuania, Latvia, Belarus, Moldova and parts of the UK (England), France, Germany, Poland, Estonia, Russian Federation, Ukraine, Romania, Bulgaria, Kazakhstan and Turkmenistan	(a) Anglo and Paris Basin, (b) Aquitaine Basin, (c) London and Brabant Platform, (d) Dutch Basin, (e) Northwest German Basin, (f) German-Polish Basin, (g) Russian Platform, (h) Ural Mountains
12: Mountains of Central and Southern Europe	Czech Republic, Slovakia, Switzerland, Austria, Hungary, Portugal, Spain, Andorra, Monaco, Italy, San Marino, Malta, Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro, Albania, Macedonia, Greece, Cyprus and parts of France, Germany, Poland, Ukraine, Romania and Bulgaria	(a) Iberian Massifs (a.o. the Hesperian Massif) and adjusted coastal plains; (b) Tajo-Duero Basin; (c) Pyrenees; (d) Massif Central; (e) Jura, Vosges and Ardennes; (f) Southern German Basins; (g) Alps; (h) Po Basin; (i) Apennines; (j) Bohemian Massifs; (k) Pannonian Basin; (l) Carpathian Mountains; (m) Dinaric Alps
13: Atlas Mountains	Parts of Morocco, Algeria, Tunisia	(a) Northern Atlas mountain range (Anti, High, Middle and Tell Atlas), (b) El-Shatout depression, (c) Saharan Atlas mountains in the South
14: Saharan basins	Morocco, Algeria, Tunisia, Libya, Egypt, Sudan, Western Sahara, Mauritania, Gambia, Guinea, Senegal, Mali, Niger, Chad	(a) Tindouf Basin, (b) Grand Erg/ Ahnet Basin, (c) Trias/Ghadames Basin, (d) Hamra Basin, (e) Sirte Basin, (f) Erdis/Kufra Basin (Nubian Sandstone), (g) Dakhla Basin (Nubian Sandstone), (h) Nile Valley and Delta, (i) Senegal-Mauritanian Basin, (j) Regubiat High, (k) Taoudeni Basin, (l) Hoggar High, (m) Iullemmeden Basin, (n) Chad Basin, (o) Tibesti (Quadai) Mountains, (p) Ennedi-Darfour

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
		Uplift, (q) Sudan interior basins (Nubian Sandstone)
15: West African basements	Mauritania, Mali, Guinea, Sierra Leone, Liberia, Burkina Faso, Ghana, Togo, Benin, Nigeria, Cameroon, Central African Republic, Equatorial Guinea, Gabon, Republic of Congo, Democratic Republic of Congo, Angola, Namibia, South Africa	(a) Eburneen Massif, (b) Volta Basin, (c) Niger Delta, (d) Nigerian Massif, (e) West Congo Precambrian Belt, (f) Damer Bel
16: Sub-Saharan basins	Republic of Congo, Democratic Republic of Congo, Angola, Zambia, Zimbabwe, Botswana, South Africa, Mozambique	(a) Congo Basin, (b) Kalahari-Etosha Basin, (c) Kalahari Precambrian Belt (Western part), (d) Karoo Basin, (e) Cape Fold Belt, (f) coastal basins of Mozambique
17: East African basement and Madagascar	Sudan, Democratic Republic of Congo, Uganda, Kenya, Tanzania, Zambia, Mozambique, Zimbabwe, Madagascar	(a) East Congo Precambrian Belt, (b) Luffilian Arch (Katanga system), (c) East Kalahari Precambrian Belt, (d) East Africa Basement (including rifted zones), (e) Tanzania coastal basin, (f) Sediments of Madagascar, (g) Basement of Madagascar
18: Volcanics of East Africa	Ethiopia, Kenya	(a) Amhara Plateau, (b) Eastern Branch of East African Rift Valley
19: Horn of Africa basins	Ethiopia, Somalia, Kenya	(a) Ogaden Basin, (b) Somali Coastal Basin
20: West Siberian platform	Russia	(a) Yenisey Basin, (b) West Siberian Basin, (c) Turgay Depression (basin)
21: Central Siberian Plateau	Russia	(a) Tunguska Basin, (b) Cis-Sayan Basin, (c) Lena-Vilyuy Basin, (d) Anabar-Olenek High, (e) Nepa-Botuoaba Arch, (f) Aldan uplift
22: East Siberian highlands	Russia	(a) Verkhoiansk Range, (b) Cherskii Range, (c) Kolyma Plain, (d) Yukagir Plateau, (e) Anadyr Range
23: Northwestern Pacific margin	Japan, Taiwan, Philippines and parts of Russia	(a) Kamchatka Peninsula, (b) Kuril Islands, (c) Japan, (d) Philippines
24: Mountain belt of Central and Eastern Asia	Parts of Russia, Kazakhstan, Mongolia and China and the	(a) The Altay-Sayan Folded Region (Central Siberia-Mongolia Border), (b) Mongol-

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
	countries North Korea and South Korea	Okhotsk Folded Region, (c) Baikal-Paton Folded Region (surroundings of Lake Baikal), (d) Aldan Shield in Eastern Siberia, (e) Yinshah Da and Xia Hingganling Uplift (Yablonovy and Khingan ranges), (f) Sikhote-Alin Folded Region (South-East Siberia), (g) Korean Peninsula
25: Basins of West and Central Asia	Turkmenistan, Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, parts of the countries China, Afghanistan, Iran (North), and Mongolia (South)	(a) Central Kazakhstan Folded Region, (b) Syr Darya Basin, (c) Tian Shan Fold Belt
		(d) Junggar Basin, (e) Tarim Basin, (f) Altushan Fold Belt, (g) Jinguan Minle Wuwei Basin, (h) Erdos Basin, (i) Shauxi Plateau, (j) Taihangshan Yanshan Fold Belt
26: Mountain belt of West Asia	Turkey, Iran, parts of Georgia, Armenia, Azerbaijan, parts of Iraq, Turkmenistan, Afghanistan and Pakistan	(a) Taurus Mountains, (b) Anatolian Plateau, (c) Caucasus, (d) Central Iranian Basins, (e) Elburz Mountains, (f) Zagros Fold Belt and Trust zone (Zagros Mountains)
27: Himalayas and associated highlands	Parts of the countries Afghanistan, Pakistan, Tajikistan, India, Nepal, China, Burma, Thailand	(a) Hindu Kush, (b) Pamir High, (c) Tibetan Plateau, (d) Himalayas, (e) Shan Plateau, (f) Tenasserim Mountains
28: Plains of Eastern China	Eastern China	(a) Manchurian Plain, (b) North China Plain, (c) middle and lower Chang Jiang (Yangtze) River Basin
29: Indo-Gangetic-Brahmaputra plain	Parts of the countries India, Pakistan, Nepal (terai) and Bangladesh and Myanmar	(a) Indus Basin, (b) Ganges Basin, (c) Brahmaputra Basin d) Irrawaddy Basin
30: Nubian and Arabian shields	Saudi Arabia, Egypt, Sudan, Ethiopia, Yemen	(a) Red Sea coastal plains (e.g. Tihama Plains), (b) North Western Escarpment Mountains (Midian and Hiraz), (c) Asir Mountains, (d) Arabian Shield (e.g. Najd Plateau), (e) Yemen Highlands
31: Levant and Arabian platform	Parts of Turkey, Syria, Lebanon, Palestine, Israel, part of Egypt, Jordan, Saudi Arabia, Iraq, part of Iran, Kuwait, Bahrain, Qatar,	(a) Sinai, (b) Euphrates-Tigris Basin, (c) Al Hasa Plain in Saudi Arabia), (d) Central arch with Tuwaig Mountains, (e) Rub-al-Khali Basin, (f) Marib and

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
	United Arab Emirates, Oman, part of Yemen	Shabwa basins in Yemen, (g) Masila-Jeza Basin (with Wadi Hadramawt), (h) Mountains and plains of Oman
32: Peninsular India and Sri Lanka	Part of India, Sri Lanka	(a) Precambrian basement areas in southern and eastern India, (b) Precambrian basement area of Aravalli Range in Rajasthan, (c) Precambrian basement and sediments of Sri Lanka, (d) Deccan Trap, (e) coastal sedimentary areas
33: Peninsulas and Islands of South-East Asia	China, Vietnam, Laos, Cambodia, Thailand, Malaysia, Indonesia, Brunei, Papua New Guinea	(a) South China Fold Belt, (b) Truong Son Fold Belt, (c) Thailand Basin, (d) Khorat Platform, (e) Tonle Sap-Phnom Penh Basin, (f) Malay Peninsula, (g) Sumatra/Java Magmatic Belt, (h) Sumatra Basin, (i) Sunda Platform, (j) Barito-Kutei Basin, (k) Sulawesi Magmatic Arc
		(l) Irian Basins, (m) New Guinea Mobile Belt
34: Western Australia	Australia	(a) Pilbara Block, (b) Yilgarn Basement Block, (c) Carnarvon Basin, (d) Canning Basin, (e) Officer Basins, (f) Eucla Basin, (g) Kimberly Basement Block, (h) Musgrave Basement Block, (i) McArthur Basin, (j) Wiso and Georgina Basins
35: Eastern Australia	Australia	(a) Gawler Ranges, (b) Great Artesian Basin, (c) Murray Basin, (d) Great Dividing Range, (e) Australian Alps, (f) Tasmania Island
36: Islands of the Pacific	New Zealand, New Caledonia (France), Solomon Islands, Federated States of Micronesia, Vanuatu, Tuvalu, Kiribati, Fiji, Tonga, Samoa, French Polynesia, Marshall Islands (USA), Northern Marianas (USA), Hawaiian Islands (USA)	(a) Bismarck-New Hebrides Volcanic Arcs, (b) Fiji Island, (c) orogenic belt of New Caledonia, (d) Axial tectonic belt of New Zealand, (e) sedimentary basins of New Zealand, (f) Pacific islands West of the American continents

Source: Modified from van Weert et al. (2009)

years. Continuous dissolution over geological times of the reservoirs containing this groundwater may have enriched the mineral contents in the groundwater. This is the reason that the groundwater salinity tends to increase with increasing depth. Genetically, the most saline groundwater bodies are either of the categories, viz. marine, terrestrial (natural), terrestrial (anthropogenic) and mixed origin (Table 1.11), as explained in detail by van Weert et al. (2009).

1.7.3 Classification and Quality Guidelines

About 97% of the total global water is brackish, while the only remaining 3% being fresh in nature. While the world's oceans are unbounded, fresh water available to mankind is virtually the most finite. To meet the food and other requirements for the ever-increasing population, irrigation 'the most important sector' uses >70% of the global fresh water withdrawals and 90% of the total consumptive uses. At global level out of the total irrigated area of ~310 million ha (Mha), 117 Mha (38%) are irrigated with groundwater (FAO 2012).

Beneath many of the world's deserts (Thar Desert of the Indian subcontinent, Arab Desert of the Middle East countries, Sahara Desert in North Africa, Kalahari Desert in Southern Africa, Atacama Desert in South America, California Desert in North America, West Australian Desert) are reserves of saline water. The information for saline water use on the global prospective is reported from about 50 countries, which are using saline water for irrigation in one or other forms. These countries are virtually from the semiarid and arid regions, except some developed nations, which make use of the wastewater for irrigation. To meet the demands of the ever-increasing population, the use of saline water in agriculture is inevitable. Therefore, we need extra research efforts in saline agriculture for the judicious use of saline and other poor-quality waters.

Usually, in practice, water often is classified into a number of discrete salinity classes. Number and names of classes, parameters to which class limits are linked (total dissolved solids (TDS) and chloride content, EC) and numerical values of class limits vary among published classifications. Freeze and Cherry (1979), based on TDS levels, classified the waters (Table 1.12).

The salinity levels are specified in terms of chloride content (mg Cl L^{-1}) or EC (μS cm^{-1} or dS m^{-1}). Approximate conversions to TDS (mg L^{-1}) from μS cm^{-1} can be made by using the respective multipliers of 1.8 and vice versa by 0.7. In this inventory the lower limit of 1000 mg L^{-1} TDS is used. Thus, when talking in this report about saline groundwater, this tacitly includes brackish groundwater and brines as well.

For assessing the quality of irrigation water, main parameters determined are salt content (EC, dS m^{-1}), sodium adsorption ratio [SAR = $Na^+/\sqrt{(Ca^{2+} + Mg^{2+})}$, mol L^{-1}], residual alkalinity [RSC = $(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$ meq L^{-1}], divalent cation ratio (DCR = $\sum M^{2+}/\sum M^{n+}$) and presence of specific ions such as NO_3, F, B and Se. Based on the characteristic features of majority of groundwater in use with the farmers in different agroecological regions and the above indices,

Table 1.11 Genetic categories and typical environment at the time of origin of saline groundwater

Main class of origin	Genetic category or salinization mechanism	Typical environment at the time of origin
Marine origin	Connate saline groundwater	Coastal zone (off-shore)
	Intruded by marine transgressions	Coastal zone (off-shore)
	Intruded by recent incidental flooding by the sea	Coastal zone (onshore)
	Laterally intruded seawater	Coastal zone (onshore)
	Intruded seawater sprays (aerosols)	Coastal zone (onshore)
	Mixture of marine and recent incidental flooding by sea	Coastal zone (on- and off-shore)
	Mixture of connate water marine transgression and recent incidental flooding by sea	Coastal zone (on- and off-shore)
Terrestrial origin (natural)	Produced by evaporation (concentration)	Shallow water table zones in arid climate
	Produced by dissolution of subsurface salts	Zone of salt tectonics or regional halite or other dissolvable formations
	Produced by salt-filtering membrane effects	At depth in thick sedimentary basins containing semipermeable layers
	Emanated juvenile water and other products of igneous activity	Regions of igneous activity
	Mixture of evaporation and dissolution	Shallow water table zones in arid climates and aquifers containing dissolvable formations
Terrestrial origin (anthropogenic)	Produced by irrigation (input of concentrated residual water)	Arid and semiarid zones; shallow depths
	Anthropogenically polluted groundwater	Anywhere on earth, particularly in modern consumptive societies
Mixed origin	Saline groundwater produced by mixing of above three classes mineralized groundwater with fresh water or with another type of saline groundwater	Anywhere on earth; hydraulic gradients facilitate the mixing processes

Source: van Weert et al. (2009)

Table 1.12 Water salinity classification based on TDS levels

Class	Class limits (TDS range, in mg L^{-1})
Fresh water	0–1000
Brackish water	1000–10,000
Saline water	10,000–100,000
Brine	>100,000

After Freeze and Cherry (1979)

Table 1.13 Classification of saline water

Water class	EC (dS m^{-1})	Salt concentration (mg L^{-1})	Type of water
Nonsaline	<0.7	<500	Drinking and irrigation
Slightly saline	0.7–2	500–1500	Irrigation
Moderately saline	2–10	1500–7000	Primary drainage water and groundwater
Highly saline	10–25	7000–15,000	Secondary drainage water and groundwater
Very highly saline	25–45	15,000–35,000	Very saline groundwater
Brine	>45	>35,000	Seawater

Source: Rhoades et al. (1992)

irrigation waters have been broadly grouped (Minhas and Gupta 1992) into good water (ECiw <2 and SAR<10), saline water (ECiw>2 and SAR<10), high SAR saline water (ECiw>4 and SAR>10) and alkali waters (ECiw variable, SAR variable and RSC>2.5). Rhoades et al. (1992) classified saline waters (Table 1.13) in terms of salt concentration, which is the major quality factor generally limiting the use of saline water for crop production.

Ragab (1998) critically examined the possibilities and constraints in the use of brackish water for irrigation and merits of sprinkler and drip irrigations for the saline water use. Kandiah (1998) derived strategies to minimize adverse environmental impacts of the saline water use in agriculture. The guidelines recommended for productive use of saline irrigation water (Minhas and Gupta 1992; Rhoades et al. 1992) are given in Table 1.14.

1.7.4 Utilization for Irrigation

In India, the use of poor-quality waters in irrigation is not new. Agriculturists, particularly in dry ecologies learnt to use these waters judiciously with care so that there is no harm to their land due to use of these waters. JW Leather reported as early as 1895 about use of poor-quality waters in his survey report (Leather 1895) and mentioned the existence of two wells in Petlad area of Gujarat just 65 m apart, one with a highly saline water and the other with good-quality water termed “sweet water” by the farmers. Farmers used the first only in the cold season and at the time of planting the crop and water of second only if the monsoon failed. They might have found that saline irrigation would be less detrimental in the cold season. They have been irrigating crops like tobacco with highly saline groundwaters when these contained substantial quantities of nitrates. In many dry regions, in the event of failure of monsoon rains or low rainfall, the cropping was done in alternate years or, in extreme cases, only in 3 years to provide for adequate salt leaching from surface soil depths (Singh 1998b). Thus, farmers had understanding of leaching down the salts developed due to saline irrigation, during rainy season. Gupta and

Table 1.14 Guidelines for saline irrigation waters (RSC <2.5 me L^{-1}) in India

Soil texture (% clay)	Crop tolerance	Upper limits of ECiw (dS m^{-1}) in rainfall (mm) region		
		<350 mm	350–550 mm	550–750 mm
Fine soil (>30%)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine soil (20–30%)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse soil (10–20%)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse soil (<10%)	Sensitive	–	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

Source: Minhas and Gupta (1992)

Abhichandani (1970) observed that 350 to 450 mm annual rainfall adequately desalinized the surface 40 cm soil depth of sandy loam to sandy clay loam soils in western Rajasthan, where farmers used highly saline irrigation waters in wheat-fallow rotation. With experience, the farmers also learnt to rotate irrigation where alternative source of water was available. Dagar et al. (2008) cultivated a cafeteria of crops in isolation and in agroforestry mode in dry areas of Hisar (annual rainfall ~500 mm) in sandy loam soils irrigating with water of EC 8–12 dS m^{-1} and found that if there was normal rainfall of the area during 1 year in 3–4 years (which always is there), there was no significant development of soil salinity in the soil profile, and one could get normal crops all through these years.

The experiences of saline irrigation have not always been happy. Jain and Saxena (1970) found accumulation of sodium and boron in the soils irrigated for 20 years with brackish groundwaters in Udaipur and Chitor districts of Rajasthan where annual rainfall is about 600 mm. In fact, saline waters are largely responsible for the widespread incidences of salinity in well-irrigated soils in Rajasthan. However, the experiences gained from the farmers' fields have helped in organizing meaningful researches on saline irrigation and in preparation of general guidelines for irrigation with waters of wide ranges of quality, soil, crop and climatic variations under average levels of management (Bajwa et al. 1975; Manchanda 1976, 1998; Ayers and Westcot 1989; Manchanda et al. 1989; Gupta 1990; Minhas and Gupta 1992; Rhoades et al. 1992; Yadav et al. 2003, 2007; Dagar and Minhas 2016). The saline water irrigation program also includes the irrigation with the drainage effluent water and the wastewater, which have been alternatively developed in many countries (Minhas et al. 2015; Yadav and Dagar 2016). Many of these studies have been basic in nature to understand ion-chemistry, specific ion toxicities, relationship with climate and salinity tolerance by different crops, while others have helped in solving the problems directly in field such as irrigation management (leaching requirement, frequency of irrigation, conjunctive use of available poor-quality water with good-quality water, fertilizer management and use of amendments such as gypsum in beds of high RAC waters. Some reports indicate that salt tolerance in plants could be increased by sowing their seeds pre-soaked in salt solution and also in some cases treating seeds with some growth hormones. Thus, many of these studies have demonstrated that waters of much higher salinities and sodicities than those customarily classified unsuitable for irrigation are being used effectively for the production of selected crops under suitable conditions. In the light of such experiences, it is, therefore, imperative to identify and give due consideration to causes and factors that make the utilization of saline groundwater an effective preposition in irrigated agriculture.

Boyko (1966) was among the pioneers to draw attention to the possibility of crop production using seawater for irrigation. Mass (1985, 1990) produced the exhaustive research data for the limits of salt tolerance in field crops, grasses and fruit crops. Based on this work, Tanwar (2003) compiled the consolidated information on salt tolerance and yield potential of selected crops as influenced by irrigation water salinity, while in India very useful information was generated on salinity limits of irrigation water for different arable crops (AICRP CSSRI, 2000–2009) particularly for arid and semiarid regions. In recent years, however, several researchers have promoted the use of halophytes and demonstrated their economic potential to produce a large and diverse number of traditional and new products using saline water including drainage and wastewaters, seawater for irrigation and marginal land resources (Dagar 2018). Recently, many salt-tolerant crops of high economic value such as medicinal and aromatic crops, and fruit-based agroforestry systems could be promoted with saline irrigation and found highly remunerative and promising, particularly in dry ecologies (Dagar 2003, 2014, 2018; Tomar et al. 2010; Dagar and Minhas 2016; Dagar et al. 2008, 2013, 2015). Many species have been domesticated for saline agriculture, and couples of chapters have been included in this volume also.

1.8 Conclusions

Existence of salt-affected soils and groundwater salinity is a widespread problem in the world. Salt problem can cause decrease in agricultural yields and profits, destroy fertile agricultural lands, cause health problems, jeopardize livelihoods, increase costs of infrastructure maintenance and costs of industrial processes and ultimately change or destroy ecosystems. All these usually depend on how much judiciously and with what procedure we use these marginal resources. With ever-increasing population and wider dependence on good-quality water for drinking, irrigation and developmental activities makes the use of poor-quality water inevitable in irrigation. Present knowledge about the use of salt-affected soils and saline water in agriculture gives a broad overview of possible technical, scientific, managerial and institutional measures that are undertaken worldwide to mitigate or adapt to their judicious and sustainable use in agriculture. To be able to manage saline soil and groundwater;

researchers, water resources specialists, policymakers and politicians need information on the scope, distribution, dynamics and severity of soil and groundwater salinity. The information given in this chapter and the entire book will contribute to provide such essential information for different stakeholders including researchers, policymakers and broader group of people to rehabilitate salt degraded resources, i.e. salinized soil and water for livelihood security of people.

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