Chapter 1
Developments in Soil Salinity Assessment, Modeling, Mapping, and Monitoring from Regional to Submicroscopic Scales

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Abstract Soil salinity spreads in more than 100 countries, and no continent is completely free from salinity. The level of salinity problem varies trans-country and even within the country at different locations, landforms, and irrigated agriculture regions to farmers' fields. Local climatic, environmental, and management conditions determine the salinity problem. Current global estimates reveal over one billion ha area affected to various degrees of soil salinization. Soil salinization in the coastal areas due to seawater intrusion developed very strongly saline soils called sabkha. Human-induced salinization occurs in irrigated agriculture farms due to poor management of soil and water resources, high water table, poor drainage conditions, and the use of saline-brackish water for irrigation with less emphasis on leaching fraction. There have been significant innovative advancements in technologies to assess, map, and monitor soil salinization spatially and temporally, from regional, national, to farm levels and submicroscopic scales. In this chapter, a comprehensive array of routine and modern techniques to address salinity issues at various scales using remote sensing and GIS, geophysical methods, and modeling are presented to guide stakeholders for the selection of appropriate technology to suit their needs and budget. A comprehensive review of such technologies and their applications has been included in this chapter, and salinity diagnostic procedures from regional to submicroscopic levels with relevant examples are described. Soil salinity classification systems used in various countries such as Australia, China, FAO-UNESCO, Russia, the USA, and Vietnam have been described. The chapter also presents global distribution of salt-affected soils.

Keywords Geophysical • GIS • Soil salinity • Submicroscopic • Thin section

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S.A. Shahid et al. (eds.), *Developments in Soil Salinity Assessment and Reclamation: Innovative Thinking and Use of Marginal Soil and Water Resources in Irrigated Agriculture*,
DOI 10.1007/978-94-007-5684-7_1,

1.1 Introduction

Soil salinity and humanity live beside each other since centuries. There is evidence in Mesopotamia that early civilizations flourished and then failed due to human-induced salinization. Parallel to population growth, such as for the last four decades, it has been doubled, by 2050 it will increase to 9 and 11 billion by 2100. In 1997, 4.8 billion of the world's 5.8 billion people (83%) were living in developing countries (FAO 1997). Soil salinization is also increasing around the world, especially in poor developing countries. The main reason of salinity increase is due to forced intensification of agriculture for short-term benefits, ignoring long-term consequences for soil services to meet food demand, and poor management of soil and water resources. Soil salinization has been identified as the major cause of land degradation. It is, therefore, very important to understand the salinity hazard spatially and temporally.

The soil salinity is dynamic, globally spreading over more than 100 countries, and no continent, even Antarctica (originally thought to be free from salinity but glaciers), is not completely free from salinity. It is a global-regional-national-ecosystem-farm level concern to all of us. It is projected that soil salinization is likely to be increased with future climate change scenarios like sea level rise and impact on coastal areas and rise in temperature that will subsequently increase evaporation and salinization. Salinization can affect ecosystem to a level where it cannot provide environmental services to its full potential.

In agriculture regions, soil salinity varies widely vertically, horizontally, and temporally, depending on such conditions as variation in soil texture, plant growth, quality of irrigation water, hydraulic conductivity, irrigation system in place. In general, salinity mapping and monitoring plan must be a part of any project dealing with the use of irrigation water with salinity/sodicity component. In agricultural farms, an effective salinity monitoring plan must be prepared to trace salinity changes particularly in the root zone to oversee the impact of management options used to overcome or reduce salinity effects and to assure that root zone salinity does not increase above crop threshold level to avoid yield losses. At the regional and national level, such monitoring program helps identify the problem and areas at risk for salinization and, hence, helps policymakers to take necessary and timely action to tackle the issue to avoid spreading to other areas that may have significant impact on national economies through degrading soil resources.

The knowledge and data gained from remote sensing of saline soils is used heavily in agricultural uses all over the world. The RS images taken over a period of time are used to (1) monitor the progress of the reclamation projects to insure the processes are being carried out accordingly and that the soil is being returned to its original condition and (2) predict areas at risk. Salinity monitoring of agricultural fields and salt-affected soils as well as sodium-bearing minerals (halite NaCl) is important to manage agriculture fields for better production. By knowing soil salinity, salt-tolerant crops, whose salinity threshold values are matching to salinity zones, can be selected to assure better behavior of crops. This is particularly important in impoverished regions where agriculture is at high risk and food shortages are a reality. The knowledge gained from the new monitoring techniques, along with that generated by decades of painstaking field research, is offering many insights to the causes of salinization. Such monitoring program, aids scientists to predict sites most at risk of waterlogging and salinization so that preventative measures such as where to establish plantation eliminate waterlogging "through biodrainage" at the areas of risk.

Monitoring determines periodic changes in soil salinity. Soil salinity mapping at the regional, national, and farm levels is becoming increasingly important for decision making and managing these resources. It is important where salinity occurs, to generate soil salinity information to determine extent and further risk of salinity, of which salinity assessment, mapping, and regular monitoring have a great role to play. Various researchers (FAO 2009) have assessed and monitored salt-affected soils at national and regional scales, for example, irrigated Arab agriculture (Abdelgawad 2009), India (Singh and Mandal 2009), Thailand (Im-Erb and Sukchan 2009), Iran (Cheraghi et al. 2009), Egypt (Gomaa 2009), China (Yang 2009), and Sudan (El-Mubarak 2009). The aim of soil salinity mapping is to know temporal subtle salinity differences in the landscape and to develop salinity zones to help design management plan for sustainable use of soil resources. Managing saline soils is highly site specific and depends on factors such as nature of soils, soluble salts, and local hydrological conditions.

In this chapter, significant efforts have been made to present review of technological advancements and their application in soil salinity assessment, mapping, and monitoring, such as remote sensing, geographical information system, modeling, geophysical, field to submicroscopic levels, and routine procedures, by giving appropriate examples, suitable to address the needs of various stakeholders at various levels (farm-national-regional scales).

1.1.1 Salinity and Sodicity Conception

To soil scientists, the concept of salinity and sodicity is crystal clear as they studied it from prep of soil science to postgraduate levels; however, experience shows that non-soil scientists many times consider salinity and sodicity of similar meaning. Definitions of both are simple and straightforward, but to clarify at all levels, they are briefly defined here.

Salinity is a measure of the concentration of all the soluble salts in soil or water as electrical conductivity (EC). From saline soil definition point of view, when EC of soil extract from saturated paste equals or exceeds 4 dS m^{-1} at 25°C, the soil is said to be saline (US Salinity Lab Staff 1954); this definition is still part of the latest glossary of soil science in the USA.

The salinity (EC) is measured as millimhos cm^{-1} (mmhos cm^{-1}), the old unit which is now obsolete. Currently used standard international (SI) units are milli-Siemens per cm (mS cm^{-1}) or deci-Siemens per meter (dS m^{-1}). The use of dS m^{-1} is preferred over the unit mmhos cm^{-1}. The units can be presented as 1 d

S m^{-1} = 1 mmho cm^{-1} = 1 mS cm^{-1} = 1,000 micro-Siemens per cm (1,000 μS cm^{-1}). Readings are usually taken and reported at a standard temperature of 25°C. For accurate results, EC meters should be checked with 0.01-N KCl solution, which should give a reading of 1.413 dS m^{-1} at 25°C.

In agricultural fields, the irrigation through flood irrigation and modern irrigation systems (drips and sprinklers) is unlikely be applied uniformly; therefore, the behavior of salinity development would be heterogeneous at the farm level. Recently Shahid et al. (2010) have hypothesized salinity development cycle to describe the sequence of soil salinity development, including various facets, such as leaching, seepage from system, water movement restriction, capillary rise, and evaporation to salts crystallization.

Sodicity is a measure of sodium ions in soil or water relative to calcium and magnesium ions. It is expressed either as sodium adsorption ratio (SAR) or as exchangeable sodium percentage (ESP). If the SAR of the soil equals or is greater than 13 (mmoles $L^{-1})^{0.5}$ or ESP equals or is greater than 15, the soil is termed sodic (Richards 1954). The SAR is calculated by the relationship $SAR = Na/[(Ca+Mg)/2]^{0.5}$, where the concentrations of Na^+ and $Ca^{2+}+Mg^{2+}$ are in milliequivalents per liter (meq L^{-1}) in soil extract from saturated paste, and SAR is expressed as (mmoles $L^{-1})^{0.5}$.

1.1.2 Global Identification of Salinity Problem

The planet Earth presents world land surface to about 13.2×10^9 ha, and within this total land, only 7×10^9 ha is arable and only 1.5×10^9 ha of which is cultivated (Massoud 1981). Of the cultivated lands, about 0.34×10^9 ha (23%) are saline and another 0.56×10^9 (37%) are sodic. Worldwide, the area of cultivated land has increased by less than 6% in the last 25 years. Older estimate (Szabolcs 1989) presents 10% of the total arable land to be affected by salinity and sodicity and extends over more than 100 countries and almost all continents. One billion ha of the 13.2×10^9 ha land on Earth is covered with saline and/or sodic soils, and between 25 and 30% of irrigated lands are salt-affected and commercially unproductive. In Southwest USA and Mexico, about 200×10^6 ha land is affected by salinity. In Spain, Portugal, Greece, and Italy, saltwater intrusion into aquifers is significant, and in Spain more than 20% of land area is desert or seriously degraded and nonproductive. In the Middle East 20×10^6 ha area is affected by increased groundwater and soil salinity, reasons being irrigation practices, high evaporation rates, growth of sabkhas (salt scalds), and increase in groundwater salinity. In addition, the irrigated lands of Euphrates (Syria, Iraq) are seriously constrained by salinity. In Iran 14.2% of the total area is salt-affected (Pazira 1999). In Egypt 1×10^6 ha cultivable land along the Nile is salt-affected; salt accumulation in Jordan River basin adversely affected agricultural production in Syria and Jordan. In Iran 25×10^6 ha land is unproductive due to salinity. In Africa 80×10^6 ha is saline, sodic, or saline/sodic, of which Sahel, West Africa, is most affected; in Asia, for example, in India, 20% of cultivable land is affected and distributed mainly in Rajasthan, coastal Gujarat, and Indo-Gangetic

Table 1.1 Distribution of salt-affected soils (Kovda and Szabolcs 1979; cf. Pessarakli and Szabolcs 2011)

Continent	Area (Million ha)
North America	15.7
Mexico and Central America	2.0
South America	129.2
Africa	80.5
South Asia	87.6
North and Central Asia	211.7
South-East Asia	20.0
Australasia	357.3
Europe	50.8
Total	954.8

plains. In Pakistan 10×10^6 ha is affected; about 5–10 ha per hour is lost to salinity and waterlogging in inland coastal regions and irrigated Indus basin. In Bangladesh 3×10^6 ha is unproductive due to salinity. In Thailand 3.58×10^6 ha is salt-affected (3.0 and 0.58×10^6 ha inland and coastal saline soils, respectively). In China 26×10^6 ha total land area is salt-affected (Inner Mongolia, Yellow River basin, tidal coastal regions), and in Australia the extent of saline soils is 357×10^6 ha.

Table 1.1 shows global distribution of salt-affected soils (Kovda and Szabolcs 1979). They are distributed in desert and semidesert regions and frequently occur in fertile alluvial plains, river valleys, coastal area, and irrigation districts. The countries where significant salinity problems exist include but not limited to Australia, China, Egypt, India, Iran, Iraq, Mexico, Pakistan, the USSR, Syria, Turkey, and the United States. In Gulf States (Bahrain, Kuwait, Saudi Arabia, Qatar, Oman, and the United Arab Emirates), saline soils mainly occur in coastal lands (due to seawater intrusion) and agriculture farms irrigated with saline-brackish water.

1.1.3 Classification of Salt-Affected Soils

Many classification systems of salt-affected soils are available in the published soil literature; the most common one is of the US Salinity Laboratory Staff (1954). Classifications most commonly used are recently described by Shahid and Rahman (2011). In this section, they are introduced briefly, with addition of saline soil classification from Australia, China, and Vietnam.

1.1.3.1 US Salinity Laboratory Staff Classification (Richards 1954)

Saline: the soil with $ECe \geq 4$ dS m^{-1} and $ESP < 15$
Saline-sodic: the soil with $ECe \geq 4$ dS m^{-1} and $ESP \geq 15$
Sodic: the soil with $ECe \leq 4$ dS m^{-1} and $ESP \geq 15$

The high ECe flocculates soils and causes physiological drought in plants, while high ESP disperses soil aggregates and affects soil permeability through structure degradation.

1.1.3.2 FAO-UNESCO Classification (FAO-UNESCO 1974)

Salt-affected soils (halomorphic soils) are also indicated on the soil map of the world (1:5,000,000) by FAO-UNESCO (1974) as solonchaks and solonetz (Russian names). Solonchaks are soils with high salinity (ECe > 15 dS m^{-1}) within 125 cm of the soil surface. The FAO-UNESCO (1974) divided solonchaks into four mapping units:

- *Orthic solonchaks* – the most common solonchaks
- *Gleyic solonchaks* – with groundwater influencing the upper 50 cm
- *Takyric solonchaks* – solonchaks in cracking clay soils
- *Mollic solonchaks* – solonchaks dark-colored surface layer, often high in organic matter

Soils with ECe between 4 and 15 dS m^{-1} are mapped as "saline phase" of other units.

The FAO-UNESCO (1974) divided solonetz (>15 ESP) into three mapping units:

- *Orthic solonetz* – the most common solonetz
- *Gleyic solonetz* – groundwater influence in the upper 50 cm
- *Mollic solonetz* – dark-colored surface layer, often high in organic matter

Soils with ESP between 6 and 15 are mapped as a "sodic phase" of other soil units.

1.1.3.3 Australian Salinity Classification (Isbell 1998)

Highly saline – soils having EC > 2 dS m^{-1} (1:5 H_2O) are considered highly saline.
Sodic – since the review by Northcote and Skene (1972), an ESP of six has been widely used in Australia as a critical limit for the adverse effects of sodicity.

1.1.3.4 Russian Salinity Classification

- *External solonchaks* – soluble salts throughout whole soil
- *Internal solonchaks* – soluble salts in subsoil or substratum only
- *Due to composition of salts* – nitrate, nitrate-chloride, chloride, chloride-sulphate, sulphate-chloride, sulphate-soda, soda, and borate
- *The external solonchaks* – flooded, puffed, sabkha
- *Origin of salts* – closed basin, marine, allochthonous air blown, anthropic

1.1.3.5 Soil Survey Staff (2010)

In the US Soil Taxonomy, true saline soils belong to the order "Aridisols" and suborder salids (equivalent to solonchak), divided into two great groups (aquisalids and haplosalids). Salids are soils which have a salic horizon within 100 cm of the soil surface.

Salic horizon – a horizon of accumulation of salts that are more soluble than gypsum in cold water

- Is 15 cm or more thick and has, 90 consecutive days or more in normal years:
  1. An electrical conductivity (EC) equal to or greater than 30 dS m^{-1} in the water extracted from a saturated paste
  2. A product of the EC, in dS m^{-1}, and thickness, in cm, equal to 900 or more

Aquisalids – soils that are saturated with water in one or more layers within 100 cm of the mineral soil surface for 1 month or more in normal years and also have a salic horizon within 100 cm of the soil surface

Aquisalids are divided into the following subgroups based on the presence of diagnostic horizon within upper 100 cm of the soil surface:

- *Gypsic aquisalids* – gypsic or petrogypsic horizon within 100 cm of the soil surface
- *Calic aquisalids* – calcic or petrocalcic horizon within 100 cm of the soil surface
- **Anhydritic aquisalids* – anhydritic horizon within 100 cm of the soil surface
- *Typic aquisalids* – which do not have characteristics of the above subgroups

*Anhydritic aquisalids subgroup has recently been identified by Shahid et al. (2007) and is currently under consideration by USDA for a change in USDA Soil Taxonomy (EAD-ICBA 2012).

Haplosalids – soils that are not saturated with water (like aquisalids) but has a salic horizon within 100 cm of the soil surface

Haplosalids are divided into five subgroups based on the presence of diagnostic horizon within upper 100 cm of the soil surface:

- *Duric haplosalids* – a duripan within 100 cm of the soil surface
- *Petrogypsic haplosalids* – a petrogypsic horizon within 100 cm of the soil surface
- *Gypsic haplosalids* – a gypsic horizon within 100 cm of the soil surface
- *Calcic haplosalids* – a calcic horizon within 100 cm of the soil surface
- *Typic haplosalids* – that do not have characteristics of the above-described haplosalids

Sodic soils are depicted at the great group level named Natrargids (argids that have natric horizon and do not have a petrocalcic horizon within 100 cm of the soil surface) which are argids (accumulation of clay) with a high ESP and are equivalent to solonetz (FAO-UNESCO 1974) or sodic soils.

1.1.3.6 Chinese Saline Soil Classification

Saline soils are classified as per weight of salts (g) per kilogram (g kg^{-1}) of soil, based on their occurrence in different landscapes and regions:

(a) *Coastal, semi-humid, semiarid, and arid regions*

- Light saline soil (1–2g kg^{-1})
- Moderate saline soil (2–4g kg^{-1})
- Severe saline soil (4–6g kg^{-1})
- Solonchaks (>6g kg^{-1})

(b) *Semidesert and desert regions*

- Light saline soils (2–3g kg^{-1})
- Moderate saline soil (3–5g kg^{-1})
- Severe saline soil (5–10g kg^{-1})
- Solonchaks (>10g kg^{-1})

In Chinese Soil Taxonomy (Chinese Academy of Sciences 2001), the following are identified:

Salic crust – has been identified as crustic epipedon with a thickness of 2 cm or more from the surface and has soluble salt contents of 100g kg^{-1} or more.
Salic horizon – accumulation of salts more soluble than gypsum and has thickness of 15 cm or more and salt content of (a) 20g kg^{-1} or more in Aridosols or Halosols of arid regions or EC (1:1) is 30 dS m^{-1} or more or (b) or 10g kg^{-1} or more in Halosols of other regions or EC (1:1) is 15 dS m^{-1} or more and product of thickness (cm) and salt content (g kg^{-1}) is 600 or more, or the product of EC (dS m^{-1}) and thickness (cm) is 900 or more.
Hypersalic horizon – a non-cemented horizon, with a thickness of 15 cm or more and salt content of 500 g kg^{-1} or more, and is loose and shows white, granular salt crystal or salt spot, when dry.
Salipan – cemented or indurated pan formed by soluble salts mainly composed of halite (NaCl). It has a thickness of 5 cm or more and soluble salt contents of 200 g kg^{-1} or more; shows platy or coarse blocky structure; and cannot be penetrated by spade or auger, when dry.

The lower limit of salt content in salic horizon is 5 g kg^{-1} (arid region) or 2 g kg^{-1} (other regions).

In Chinese Soil Taxonomy, saline soils are identified at the third level of order Aridosols:

Order – Aridosols
Suborder – Orthic Aridosols
Group – Sali-Orthic Aridosols (having a salic, hypersaline horizon or salipan, which has its upper boundary within 100 cm of the soil surface)
Subgroups – at Sali-Orthic Aridosols great group level; lithic, sodic, gypsi-panic, panic, gypsic, and typic (Sali-Orthic Aridosols) subgroups have been identified

1.1.3.7 Vietnam Saline Soil Classification

Saline soils are classified as per weight of salts (g) per kilogram (g kg^{-1}) of soil:

- Light saline soils (2.5–5 g kg^{-1})
- Moderate saline soil (5–10 g kg^{-1})
- Strong saline soil (>10 g kg^{-1})
- Solonchaks (>10 g kg^{-1})

1.1.4 Socioeconomic and Environmental Impacts of Saline Soils

(a) *Low Production and Socioeconomic Impacts*

- Farm abandonment reduces number of farmers and causes socioeconomic disturbance
- Low production due to low response to inputs leads to economic losses
- High cost for soil reclamation
- Loss of good quality soil (organic matter, nutrients) requires more input like fertilizer, financial pressure on farmer
- Compromised biosaline agriculture system that may give less cash returns compared to conventional crop production systems
- Farmers' migration to urban area

(b) *Environmental Impact*

- Ecosystem fragmentation
- Poor vegetation leads to soil degradation (erosion)
- Dust causes environmental issues
- Sand encroachment in productive areas
- Storage capacity of reservoirs reduced
- Contamination of groundwater

1.2 Salinity Diagnostics at Regional to Submicroscopic Levels: Scientific Antecedents

In the following section, a comprehensive review is given on currently used advanced technologies in soil salinity assessment, modeling, mapping, and monitoring. Salinity diagnostic procedures are also briefly described supported by examples.

1.2.1 Remote Sensing and Geographical Information System

Salinity mapping can be accomplished by various techniques integrating remote sensing (RS) and GIS at broad and small scales. Combining information on these and other factors could allow the prediction of sites vulnerable to the saline menace. This is where a geographic information system (GIS) can play a role. GIS is a computer application that involves the storage, analysis, retrieval, and display of data that are described in terms of their geographic location. The most familiar type of spatial data is a map – GIS is really a way of storing map information electronically. A GIS has a number of advantages over old-style maps, though; one is that because the data are stored electronically, they can be analyzed readily by computer. In the case of salinity, scientists can use data on rainfall, topography and soil type – indeed, any spatial information that is available electronically – to first determine the combinations most susceptible to salinization and then to predict similar regions that may be at risk. RS imagery is well suited to map the surface expression of salinity (Spies and Woodgate 2004), for example, poor vegetation cover could be an indication of salinity in the area, while depth to groundwater and associated vegetation cover is widely regarded as the most useful indicator for determining salinity trends and risks. The goal of such exercise is to assess and map soil salinity to understand the problem, provide information to take necessary action to prevent its temporal distribution, and to manage the improvement and sustainable use of land resources. Salinized and cropped areas can be identified with a salinity index based on greenness and brightness that indicates leaf moisture influenced by salinity, with classical false-color composites of separated bands or with a computer-assisted land-surface classification (Vincent et al. 1996). A brightness index detects brightness appearing at high levels of salinity. Satellite images can help in assessing the extent of saline areas and monitoring the changes in real time. Saline fields are often identified by the presence of spotty white patches of precipitated salts. Such precipitates usually occur in elevated or unvegetated areas, where water evaporates and leaves salt behind. Such salt crusts, which can be detected on satellite images, are not reliable evidence of high salinity in the root zone. Inadequate resolution of low-cost RS data in optical range limited the identification to surface salt encrustation; therefore, identification of subsurface salinity and waterlogging using optical RS data becomes difficult. Another limitation in salinity mapping with multispectral imagery is where saline soils support productive plant growth (Furby et al. 1995) such as biosaline agriculture, where plant cover obscured direct sensing of the soil, while salt-tolerant plants could not be differentiated from other cover, unless extensive ground truthing is made to correlate the information.

RS can provide useful information for large-area water and salt balances and identification of parameters such as evapotranspiration, rainfall distribution, interception losses, and crop types and intensities that can be used as indirect measures of salinity and waterlogging and as evidence for direct estimates (Ahmad 1999). Salinity mapping and monitoring through using remote sensing and GIS have been common in many countries; such procedures have recently been used in Kuwait and

Abu Dhabi Emirate as part of the National Soil Inventories (KISR 1999a, b; Shahid et al. 2004; EAD 2009; Abdelfattah et al. 2010). At the regional and national levels (Sukchani and Yamamoto 2005), RS and GIS for waterlogging and salinity monitoring (Asif and Ahmad 1999), RS technology for soil salinity mapping in the Middle East (Hussein 2001, 2003), mapping salt-affected soils using RS and GIS (Maher 1990), mapping salt-affected soils using Landsat satellite data (Joshi and Sahai 1993), soil salinity mapping using airborne remote sensing and spectroscopy (Bennett 1998), salinity assessment using RS techniques (Brena et al. 1995), salinity assessment by combined use of RS and GIS (Casas 1995), multispectral remote sensing of saline seeps (Chaturvedi et al. 1983), detecting saline soils with video imagery (Everitt et al. 1988), selection of the best possible Landsat TM band combination for the delineation of salt-affected soils (Dwivedi and Rao 1992), delineation of salt-affected soils through digital analyses of Landsat MSS data (Singh and Dwivedi 1989), application of multitemporal Landsat data for salinity identification (Farooq and Ud Din 1980; Makin 1986), salinity monitoring using RS and GIS (Goossens et al. 1993), use of remote sensing in salt marsh biomass and stress detection (Hardisk et al. 1983), RS study of salt-affected soils (Mougenot et al. 1993; Verma et al. 1994), Landsat imagery for mapping saline soils (Sharma and Bhargawa 1988), application of Landsat imagery for monitoring soil salinity trends (WAPDA 1984), integration of RS and conventional information (Zevenbergen 1990), and integration of RS/GIS and spatial statistics provided useful tools for modeling variability to diagnose pattern of characteristics (Kalkhan et al. 2000). Delineation of saline soils using RS/GIS has been proven efficient in recent studies (Sharma and Bhargawa 1988; Rao et al. 1991; Dwivedi 1992; Srivastava et al. 1997; Dwivedi and Sreenivas 1998; Khan and Sato 2001).

The TM bands 5 and 7 are frequently used to detect soil salinity or drainage anomalies (Mulders and Epema 1986; Menenti et al. 1986; Zuluaga 1990; Vincent et al. 1996); broadscale monitoring of salinity using satellite remote sensing (Dutkiewics and Lewis 2008). Metternicht and Zink (1996) have shown Landsat TM and JERS-ISAR data (visible and infrared regions) the best to distinguish saline, alkaline, and nonsaline soils, and Dwivedi (1992) used Landsat SMM and TM data for detailed mapping and monitoring of saline soils in India in the frame of the reconnaissance soil map.

Abdelfattah et al. (2009) developed a model that integrates remote sensing data with GIS technique to assess, characterize, and map the state and behavior of soil salinity. The coastal area of Abu Dhabi Emirate, where the issue of salinity is a major concern, has been used as a pilot study area. The development of the salinity model has been structured under four main phases: salinity detection using remote sensing data, site observations (ground truthing), correlation and verification (intersection between salinity map produced from visual interpretation of remotely sensed data and salinity map produced from site observations), and model validation. GIS was used to integrate the available data and information, to design the model, and to create different maps. A geodatabase was created and populated with data collected from observation points together with laboratory analyses data. The results of the study indicated that the correlation between the salinity maps developed from remote sensing data and site observations shows that 91.2% of the saline areas delineated using remote sensing data fit with those delineated using site observations data. The study confirmed that ground truthing coupled with RS data and GIS techniques are powerful tools in detecting salinity at different levels in hyperarid conditions and hence the model can be adopted elsewhere in similar areas that experience salinization problems.

1.2.2 Modeling

Salinity is dynamic and transient condition in saline soils. Chemical reactions in root zone (solubility, precipitation, cation-exchange reactions) in irrigated field affect soil salinity and sodicity and salt contribution to drainage water. Comphuter programs (Dutt and Tanji 1962; Dutt 1962) can predict composition of soil solutions. Others (Oster and Rhoades 1975; Rhoades and Suarez 1977) used models to evaluate salinity, sodicity, and environment hazards of drainage water that resulted from irrigation; others calculate the effect of chemical reactions in the soil solution composition for transient conditions within the root zone (Jury et al. 1978; Robbins et al. 1980) and for sodic soil reclamation (Dutt et al. 1972). There exist models to address salinity issues in agriculture fields and landscapes vulnerable to soil salinization and try to give answer to specific questions. Numerical models can be used as evaluation tools in predicting soil and water salinity-related-dependent variables that help in decision making. In addition, model results assist in evaluating possible scenario analysis. Models that incorporate all governing elements of nature such as soils, water, crops, and agrometeorology produce better results as they represent the nature to a large extent. One limitation of such holistic models is extensive data requirements. The potential numerical models, however, need to be locally calibrated and validated for reliable application of model outputs. Modeling soil-water-salt-plant relationships is important for the use of scaling and extension of technologies and decision support system. How models can be made to predict near to the actual field conditions is essential in modeling development. Since several factors beyond the problems considered in these models play significant deciding role in biological systems like agriculture, issues like climate change and its likely impacts in saltwater dynamics under actual condition should be considered (FAO 2009). In the First Expert Consultation on Advances in Assessment and Monitoring of Salinization for Managing Salt-Affected Habitats (FAO 2009), it was concluded that salinity models could be of limited use if they are not well designed and some models can be very vulnerable to particular parameters if not properly developed. Comparison of two models (SMSS2 and SMSS3) with reference to irrigation-induced soil and water quality parameters was presented from Morocco. The statistical results from the model outputs supported the reliable use of models. Soil physics character should be studied for reliable prediction models. It was recommended that SWAP model has been efficiently used and needs to be shared with network member countries. Limitation of using modeling under saline conditions is due to the dynamic nature of salinity problems which should be clearly understood by the model users. Physically based models simulating water and solute transport represent an essential tool for predicting soil salinity and/or sodicity. These models enable different options to be compared to develop strategies for sustainable irrigation in the short and in the long term. However, calibration and validation of these models against soil and crop field data is needed to check accuracy of the predicted values before these models can be used to develop reliable management scenarios.

Models could be simple or of great complexity. Major constraint to these models is mostly the lack of input data; many times, assumptions are made on different data to run these models (Ranatunga et al. 2008). Some models are simple, for example, Watsuit model (Rhoades and Merrill 1976) considers water composition, leaching fraction, and presence and dissolution and precipitation of minerals like calcite and gypsum in the root zone. The dissolution and precipitation of minerals can change water composition and quality; the relative magnitude of such effects can be evaluated by using Watsuit calculations; details of the assumptions and relations that comprise this model are given in Rhoades (1972, 1977, 1984, 1987, 1988) and Oster and Rhoades (1990).

Noncomputer version of Watsuit can be used where computer facilities are lacking in an analogous way to the computer-based Watsuit to predict the likelihood of soil water salinity-, sodicity-, and toxicity-related problems resulting from irrigation under steady-state conditions. However, these predictions are less accurate than computer-based Watsuit predictions. This can be achieved by multiplying the water EC with factors (fc) appropriate to leaching fraction and root zone salinity; these factors are described by Rhoades (1992). While considering Watsuit as a "production-function model," the effect of salinity on evapotranspiration (ET) is not taken into account, rather, it is assumed that there will be no yield loss, hence in ET, so long as the threshold level of ECe is not exceeded; thus, water suitability is simply predicted to learn whether the predicted salinity from irrigation will exceed ECe or not.

The models that consider water flow, water uptake by crops, and solution chemistry can allow more realistic simulation of the soil water status. There are very limited numbers of models that consider such aspects; among these models are the LEACHM (Hutson and Wagenet 1990) and UNSATCHEM (Suarez and Simunek 1997). A major limitation to the use of the LEACHM model is that it is not able to simulate sodic, alkaline conditions (Suarez and Dudley 1998). The UNSATCHEM 3.0 model (Suarez and Vaughan 2002) considers variably saturated water flow, heat flow, plant water uptake, and solution chemistry including cation exchange, precipitation-dissolution of mineral phases, and boron adsorption.

Models that can be used for a variety of irrigation systems, soil types, soil stratification, crops and trees, water application strategies (blending or cyclic), leaching requirement, and water qualities are lacking. For that purpose, the SALTMED model has been developed (Ragab 2001). The model employed the well-known water and solute transport, evapotranspiration, and crop water uptake equations. The FAO-US Salinity Laboratory SWS (Suarez and Vaughan 2002) developed a model (soil/water quality model) to evaluate the suitability of water for irrigation, primarily in arid and semiarid regions. The suitability of water is evaluated in terms of its utility for crop growth. The FAO-US Salinity Laboratory soil water quality model is a modification of the UNSATCHEM model (Suarez and Simunek 1997; Simunek and Suarez 1997b). The modifications include additions to the plant module, nitrate transport and provision for calculation of ETc, upgrade to 32 bit, and a user-friendly Windows 95 interface, including default parameters and catalogue menu. The complexity of the UNSATCHEM model, which was developed as a research tool, is greatly reduced in the FAO-US Salinity Laboratory model by means of the default parameters, set by the interface and thus hidden from the user. The UNSATCHEM model in turn is based on the SOILCO2 model (Simunek and Suarez 1997a) with addition of a chemical specification routine (Suarez 1977), calculation of exchangeable cations as described in Robbins et al. (1980), and calculation of osmotic activity coefficient using the Pitzer routines of GMIN (Felmy 1990).

Some workers compared steady-state models with transient models (Corwin et al. 2007) to optimize LF under salinity risk. A comprehensive review of models emphasizing irrigation management using saline waters has been made by Bastiaanssen et al. (2007). Batlle-Sales (2009) has given an overview of salinity modeling approaches at different spatial-temporal scales Batlle-Sales (2013). Recently Batlle-Sales (2013) described soil salinity models, approaches, and associated key issues.

1.2.3 Geostatistics

Geostatistics is used for mapping of surface features from limited sample data and the estimation of values at unsampled locations. Geostatistics is widely used in fields where "spatial" data is studied. Geostatistical estimation is a two-stage process: (1) studying the gathered data to establish the predictability of values from place to place in the study area, this study results in a graph known as a semi-variogram which models the difference between a value at one location and the value at another location according to the distance and direction between them, and (2) estimating values at those locations which have not been sampled. This process is known as "kriging." The basic technique, "ordinary kriging," uses a weighted average of neighboring samples to estimate the "unknown" value at a given location. Weights are optimized using the semi-variogram model, the location of the samples, and all the relevant interrelationships between known and unknown values. The technique also provides a "standard error" which may be used to quantify confidence levels.

In mining, geostatistics is extensively used in the field of mineral resource and reserve valuation – the estimation of grades and other parameters from a relatively small set of borehole or other samples. Geostatistics is now widely used in geological and geographical applications. However, the techniques are also used in such diverse fields as hydrology, ground water, soil salinity mapping, and weather prediction.

1.2.4 Electromagnetic Induction

The last 30 years has revolutionized soil salinity assessment. These revolutions have been in RS/GIS and development of a number of electromagnetic induction (EMI) instruments for providing reasonable in situ estimates of salinity (Corwin and Rhoades 1982; Slavich 1990). The apparent electrical conductivity (ECa) measured by EMI can be rapidly measured on a second-by-second basis; therefore, data population is relatively large, and landscape or farming land can be covered more comprehensively in short time than by conventional survey tools and methods. As larger volume of data is recorded at relatively larger spatial resolution, EMI surveys are considered as high-intensity surveys. Therefore, salinity maps prepared from ECa provide higher level resolution than those prepared from conventional surveys (Jaynes 1995), which further stated that ECa maps can be used as surrogates of soil maps. The ECa patterns in existing soil map can provide additional details (Hedley et al. 2004). A major contribution of EMI to soil surveys has been the identification and delineation of small included areas of dissimilar soils within the soil polygons (Fenton and Lauterbach 1999) and the general distribution of soils within fields (King et al. 2005). EMI has been successfully applied in high-intensity soil mapping in northern Illinois (Doolittle et al. 2009).

Spatial distribution of soil salinity on field (Cameron et al. 1981), agricultural farms (Norman et al. 1995a, b), district (Vaughan et al. 1995), and regional (Williams and Baker 1982) scales has been described. The risk of soil salinization in a vineyard at Sicilian was assessed using EM38 (Crescimanno et al. 2009), assessing salinity changes in natural landscapes and agricultural fields (Morales and Batlle-Sales 2009), integration of RS imagery and EMI was to assess soil salinity, drainage problems, and crop yield (Madrigal and Meraz 2009).

Baerends et al. (1990) used Geonics EM38 for a detailed salinity survey in an experimental area of 37 ha. The ECa is a weighted, average conductivity measurement to a specific soil depth (Greenhouse and Slaine 1983). The ECa is influenced by the type and concentration of ions in solution, the amount and type of clays, the volumetric water content, and the temperature and phase of the soil water (McNeill 1980); in general ECa increases with the increase of soluble salts and/or clay contents (Kachanoski et al. 1988; Rhoades et al. 1976). Baerends et al. (1990) found good agreement between the EM38 survey and the results of the visual agronomic salinity survey. However, they reported that the EM38 survey yields results with a better resolution; it is more sensitive to salinity changes and can be carried out at any time of the year. Rhoades (1995) reported a good agreement between the measured salinity levels and those predicted from the EM38 sensor on an average root zone (0–1.2 m) salinity levels (ECe) along the transact in the irrigated alfalfa. Williams and Baker (1982) recognized the possibility of using EM meters for reconnaissance surveys of soil salinity variation. The high values of apparent electrical conductivity (ECa) measured by the EM meters were correlated with increased amounts of salts in the soil. The correlation led to empirical relationships (Rhoades et al. 1989a, b; Cook et al. 1992; Acworth and Beasley 1998) that allow a prediction of soil salinity based on the measurement of the ECa. Presently, the devices are used regularly for soil salinity surveys in different parts of the world (Norman et al. 1989; Job et al. 1987; Williams and Hoey 1987). The main advantages of the EM method are the following: (1) measurements can be taken almost as fast as one can walk from one measurement location to another and (2) large volume of soil which is measured reduces the variability so that relatively few measurements yield a reliable estimate of the mean field salinity.

For the detection of vertical ECa changes in soil profiles from aboveground EM measurements, many investigators have used empirical relations (Cook and Walker 1992; Corwin and Rhoades 1982, 1984; Rhoades and Corwin 1981; Rhoades et al. 1989a, b) and, in one case, theoretical response functions for homogeneous profiles (Slavich 1990). All of these studies have been based on the assumption of linearity. Rhoades and Corwin (1981) and Slavich (1990) used multiple linear regressions to correlate EM ground conductivity meter readings with measured soil electrical conductivity profiles. The resulting coefficients could be used to predict soil electrical conductivity profiles at points where direct measurements were unavailable. Such regression models proved to be site specific. Hence, these relations yield reasonable results at the locations for which they have been developed or at locations with similar characteristics, but they cannot be extrapolated to sites with different characteristics without calibration. For reliable use, the instrument needs phasing and instrument zeroing using the manufacturer's standard calibration method after a warm-up period of 1 h. Calibration of the EM38 requires that the instrument in the V-VEM38 mode reads twice the ECa value of the instrument in the H-HEM38 mode when held 1.5 m above the Earth surface.

1.2.5 Micromorphological and Submicroscopic Investigations

According to Kubiena (1938), Nicol was the first to prepare thin sections of minerals in 1827. However, the method in general use today (Fitzpatrick 1984) was developed by Sorby in 1859. The concept of applying microscopic techniques in soil science was independently conceived by Kubiena (1931) and Harrison (1933). Soil thin section is an approach of studying undisturbed soil material with the aid of microscopic techniques (micromorphology). This permits study of different constituents and allows their natural relation in space and as far as possible in time to be studied. Consequently, it has become an important tool for investigations into the genesis, classification, and management of soils. Thin-section investigation by the optical microscope (OM) only provides two-dimensional (2D) information about the general soil fabric; its optical resolution imposes a limit at fine silt-sized material. The observation in the OM can be extended to clay-sized material where, for example, preferred orientation results in aggregate birefringence. The detailed micromorphology (2D) of arid and semiarid soils generally and of gypsum specifically has been presented by Stoops et al. (1978).

It has long been recognized that investigation of salt efflorescences/salt crusts from salt-affected soils has not been subjected to extensive studies (Stewart 1963) owing to their lack of economic significance and the reason that most of the salt minerals are dissolved during the process of thin-section preparation. Feofarova (1940, 1958) gave the first basic information on the salts in the soil. Driessen and Schoorl (1973) were the first to apply scanning electron microscopy (SEM) to identify minerals in salt efflorescences on saline soils. Some of the first SEM micrographs of halite were published by Driessen (1970) in his study on salt crusts from the Great Konya Basin, Turkey. In very few publications, such aspects have been studied in detail (Eswaran et al. 1980; Hanna and Stoops 1976; Barzanji and Stoops 1974; Shahid 1992; Shahid et al. 1990, 1992; Shahid and Jenkins 1994; Shahid and Mufti 1994). Braitsch (1962) brought the realization that salts occur as minerals during a large part of the year; which mineral forms and which vanishes during different seasons has been realized by Garrels and Christ (1965). Studies on evaporites (Stewart 1963) have clearly shown a salt succession which may be cyclic; some view (Kovda 1946) that the presence of salts depends on diurnal fluctuation. Muller and Irion (1969) reported a special growth structure of halite in salt sediments, salt flakes at the surface water layer of basin, large halite crystals on the bottom, and smaller ones on top of the discs. Gypsum, halite, aragonite, calcite, and huntite mineral assemblage has been reported in Tuz Golu in Turkey (Irion 1970). Review of Donar and Lynn (1971) on carbonate, halide, and sulfide minerals in soils gives the average of these salt crusts. Needle-shaped macroscopic thenardite (Na_2SO_4) crystals have been reported in puffed solonchaks (Buringh 1979) and thenardite efflorescences on polar desert soils of Prince Patrick Island (Tedrow 1966). Gumizzio et al. (1982) reported mineralogical composition of salt efflorescences in a typic salorthids. Stoops et al. (1978), using SEM, studied some authigenic sulfate minerals in soils. Different forms of gypsum have been reported by Stoops et al. (1978) and recently by Shahid and Abdelfattah (2009). While evaluating the salt morphologies by SEM (SEM and BSEI, SEM/EDXRA) and XRDA and chemical composition, Vergouwen (1980) observed that halite is forming smooth crust sealing the soil; trona, bloedite, and hexahydrite make the salt crust very fluffy.

A few micrographs of soluble minerals (gypsum and jarosite) have been published by Cheverry et al. (1972), and Eswaran and Barzanji (1974) reported gypsum micrographs. Shahid and Abdelfattah (2009) presented polymorphism of gypsum from coastline of Abu Dhabi Emirate. Hanna and Stoops (1976) have described halite cutans in saline soils from Egypt. Eswaran and Carrera (1980) used the XRD, SEM, and chemical analyses to evaluate salt profiles in two Aridisols in Peru. Eswaran et al. (1980) established halite morphologies in salt crusts using SEM. Shahid et al. (1992) by the very first time in the soil history of Pakistan revealed eight types of halite morphologies "polymorphism" using SEM and EDXRA techniques. Pioneer work on the salt-affected soils of Punjab, Pakistan, revealed dominance of thenardite minerals contrary to older hypothesis of halite dominance (Shahid 1988; Shahid et al. 1990; Shahid and Jenkins 1994). Further submicroscopic studies (SEM/EDXRA) on salt crusts from Pakistan confirmed the thenardite dominance (Shahid 1992; Shahid and Mufti 1994).

The very first in the history of soil research in Pakistan, a comprehensive study on the soil micromorphology of salt-affected soils from Punjab was completed

(Shahid 1988). The study was completed as a full requirement of a Ph.D. degree program at the School of Agricultural and Forest Sciences, University College of North Wales, Bangor, UK. Among many innovative findings, the most important and noble finding was the recognition that salt-affected soils of Punjab are dominant in thenardite (Na_2SO_4) and mirabilite ($Na_2SO_4.10H_2O$) salinity in contrast to old hypothesis of halite (NaCl) dominance. This gives new directions to researchers to focus screening of crops against Na_2SO_4 salinity to address the issues of salt-affected soils in Punjab, Pakistan. The new findings were a result of investigation of salt crusts collected from many areas of Punjab province of Pakistan using a combination of techniques including routine solution chemistry, description of thin section under optical microscopy, scanning electron microscope supplemented with energy dispersive x-ray analyses (EDXRA) for microchemical analyses, XRD, line scanning, and elemental mapping through electron probe microanalyses (EPMA). These findings also opened the door for using KCl fertilizer as source of K, rather than K_2SO_4; the latter is more expensive and largely imported in Pakistan and will enhance SO_4 toxicity in soils.

The literature on soil feature initially studied in thin section (2D) using optical microscope and further investigation by SEM (3D) through removing resin by low-temperature ashing is very scanty. The combination of OM and SEM evaluation of thin sections has attracted only limited attention (Jenkins 1980; Price and Jenkins 1980). These features can be inferred by the OM, but their 3D morphological details and their microchemical composition can only be possible at submicroscopic level. The SEM has become equally important in examining soil microfabrics (Jenkins 1980; Price and Jenkins 1980), where investigation of soil microfabrics is extended down to the submicroscopic level through low-temperature ashing (LTA) technique. The LTA is a technique whereby the impregnating resin from thin sections can be removed at low temperature through oxidation and volatilization. This technique permits features already studied under the optical microscope to be studied with the SEM at high magnification and their 3-dimensional (3D) morphology obtained. In addition, the features of interests can be analyzed with energy dispersive x-ray analyzer (EDXRA), thus giving a fairly comprehensive set of information about the feature of interest.

1.2.5.1 In Situ Elemental Mapping in Saline Features by Electron Probe Microanalyses (EPMA)

The electron microscope supplemented with energy dispersive x-ray analyses (EDXRA) or wavelength dispersive x-ray analyses (WDXRA) provides elemental composition in a soil feature at larger scale. The principle in such elemental composition is that the imaging and analytical functions of all microscopes are a direct consequence of the complex spectrum of events that always accompany the interaction of a stream of energetic electron with a solid sample. Electron-specimen interaction often yields different types of electrons and electromagnetic waves (of which x-rays are but one type) as a result of elastic or inelastic scattering events (Morgan 1985). The x-ray photons generated contain chemical information about the specimen. The x-ray mapping is a potentially useful means of qualitatively assessing the gross distribution of an element in a specimen (white dots). High-resolution x-ray dot maps can be obtained for different elements. These dots show the distribution of the elements in the feature, and their intensity is a measure of the concentration of the element. Saline soil features (highly polished thin section) can be investigated by EPMA using JEOL JXA 3A equipment (or latest models) operated at 20- and 10-kv accelerating voltage and about 0.15-μA specimen current and producing x-ray distribution pattern on a cathode ray oscilloscope (CRO) screen and photographed on a polaroid film.

1.3 Soil Salinity Diagnostic Procedural Matters: Regional to Submicroscopic Scales

Use of reliable methods for salinity diagnostics is essential to zone salinity at regional, national, farm, and even submicroscopic levels of investigation. This allows understanding of subtle difference for more precise management. Conventional soil salinity assessment requires geo-referenced field sampling and laboratory analysis where the electrical conductivity of soil saturation extract (ECe) is measured and, using GIS tool salinity zones, can be delineated. Other quicker methods have been developed such as use of RS imagery and geophysical methods (EM38) for salinity diagnostics. The EM38 is useful for agricultural salinity surveys. It is a rapid, mobile technique for measuring bulk soil electrical conductivity. It provides 1.5-m and 0.75-m depth of exploration of the vertical and horizontal dipole modes, respectively.

There are five basic tools for salinity assessment: (1) remote sensing and GIS, (2) conventional soil analyses, (3) geophysical methods, (4) salinity modeling, and (5) morphological and microchemical assessment from field to submicroscopic levels. The following section describes the technologies as well as their application in salinity aspects.

1.3.1 Remote Sensing

Remote sensing is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information. In much of remote sensing, the process involves an interaction between incident radiation and the targets of interest. This is exemplified (Shahid et al. 2010) by the use of imaging systems where the following seven elements are involved (Fig. 1.1):

1. Energy source or illumination (*A*) – the first requirement for remote sensing is to have an energy source which illuminates or provides electromagnetic energy to the target of interest.
2. Radiation and the atmosphere (*B*) – as the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes

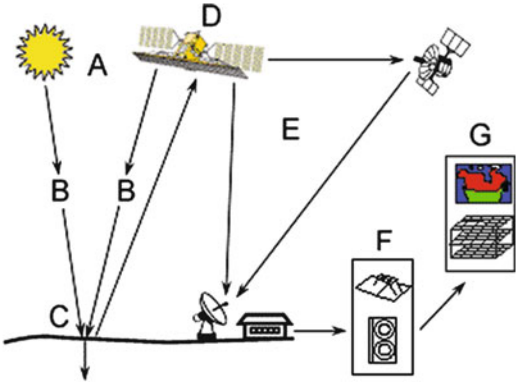

Fig. 1.1 Sequence of RS imaging system

through. This interaction may take place a second time as the energy travels from the target to the sensor.

3. Interaction with the target (*C*) – once the energy makes its way to the target through the atmosphere, it interacts with the target, depending on the properties of both the target and the radiation.
4. Recording of energy by the sensor (*D*) – after the energy has been scattered by or emitted from the target, it requires a sensor (remote – not in contact with the target) to collect and record the electromagnetic radiation.
5. Transmission, reception, and processing (*E*) – the energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image (hardcopy and/or digital).
6. Interpretation and analysis (*F*) – the processed image is interpreted, visually and/or digitally or electronically, to extract information about the target which was illuminated.
7. Application (*G*) – the final element of the remote sensing process is achieved when we apply the information we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem. These seven elements comprise the remote sensing process from beginning to end.

The RS imagery is then interpreted for both unsupervised classifications. It identifies natural grouping or structures within multispectral data. This can be accomplished by clustering methods defined with a clustering algorithm, which often uses all or many of the pixels in the input data file for its analysis. The cluster algorithm has no regard for the contiguity of the pixels that define each cluster. The ISODATA cluster method uses spectral distance as in the sequential method but iteratively classifies the pixel, redefines the criteria for each class, and classifies it again. Supervised classification is the process of using samples of known identity to classify pixels of unknown identity. Samples of known identity are those pixels located within training areas (the user selects pixels that represent recognized pattern or land cover features). The use of RS and GIS in salinity mapping has been very well described by Shahid et al. (2010), and global work is reviewed in earlier section.

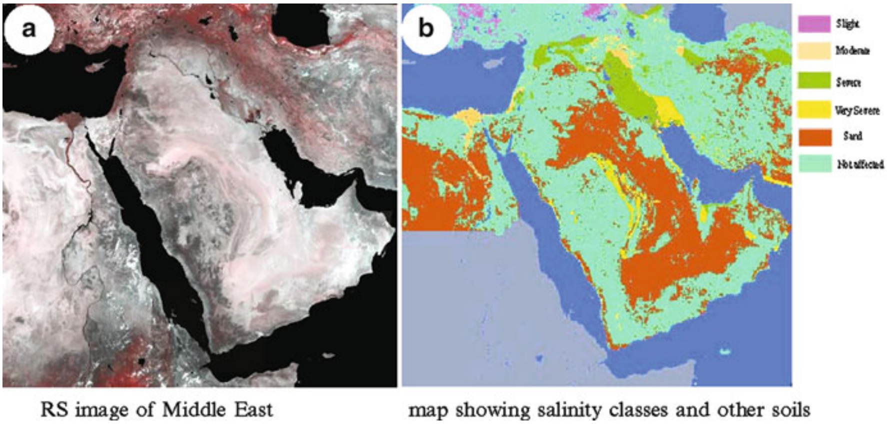

Fig. 1.2 RS image of Middle East (**a**), map showing salinity classes and other soils (**b**)

1.3.1.1 Case Study: Salinity Mapping at Regional Level (cf. Shahid et al. 2010)

As a part of more comprehensive investigation of the Middle East, Hussein (2001) investigated soil salinization in the region. He uses RS imagery and other parameters to develop soil salinization map of the Middle East (Fig. 1.2). The study focuses on the salinization affecting irrigated lands, so it is important to evaluate what is called the intensity of irrigation. For this evaluation, it is possible to use two interesting indicators. The FAO (1997) shows that in all countries, the rate of use of the equipped area for irrigation was greater than 50%.

To divide the salinization map into four classes or degrees of importance, it is necessary to establish threshold values; to achieve this task, reference is made to the existing information leading to the following threshold values. The analyses revealed 11.2% of the Middle East soils are affected by various levels of soil salinization (Table 1.2). Shahid et al. (2002) reported an area of about 12.1% to be affected to varying degrees of soil salinity in Kuwait, of which 4.37% of area is identified as inland salinity and the rest is coastal salinity.

1.3.2 Geophysical Method

Geophysical methods (especially electromagnetic induction) are gaining importance in agriculture salinity surveys. The EM38 measures salinity by transmitting an electric current through the soil; the resulting electromagnetic field is measured by a sensor in the device. This type of EC sensor works on the principle of electromagnetic induction (EMI). EMI does not contact the soil surface directly. The instrument is composed of a transmitter and a receiver coil usually installed at opposite ends of a nonconductive bar located at opposite ends of the instrument.

Table 1.2 Level of salinization and threshold values in Middle East (Hussein 2001; cf. Shahid et al. 2010)

Level of salinization	Threshold value	Area km^2	Area %
Non affected area	–	3,805,679	57.53
Slight salinization	0–25	113,814	1.72
Moderate salinization	25–75	109,148	1.65
Severe salinization	75–150	380,025	5.74
Very severe salinization	>150	138,204	2.09
Sand	–	2,068,092	31.26

EM38 works only with a fixed frequency and has an effective measurement depth of 1.5 m in vertical dipole mode or 0.75 m in horizontal dipole mode (Fig. 1.3a). The EM38 is designed to be particularly useful for salinity surveys in agricultural fields. It has gained acceptance due to its simplicity, reliability, rapidity, and reproducibility of the results. It is also a rapid, mobile instrumental technique for measuring bulk soil electrical conductivity as a function of spatial position on the landscape. Salinity maps help farmers to understand subtle difference in soil properties across their fields, allowing them to develop more precise management zones and, ultimately, potentially higher yields.

The conduction of electricity in soil takes place through the moisture-filled pores that occur between individual soil particles. Therefore, the EC of soil is determined by the following soil properties. The greater the soil porosity, the more easily electricity is conducted. Soil with high clay content has higher porosity than sandy soil. Compaction normally increases soil EC. Dry soil has much lower conductivity than moist soil. Increasing concentration of electrolytes (salts) in soil water will dramatically increase soil EC. Mineral soil containing high levels of organic matter (humus) and/or 2:1 clay minerals such as montmorillonite, illite, or vermiculite (high cation-exchange capacity) has a much higher ability to retain positively charged ions (such as Ca, Mg, K, Na, NH_4, or H) than soil lacking these constituents. The presence of these ions in the moisture-filled soil pores will enhance soil EC in the same way that salinity does. As soil temperature decreases toward the freezing point of water, soil EC decreases slightly. Below freezing, soil pores become increasingly insulated from each other, and overall soil EC declines rapidly. It should be remembered that EMI provides ECa (apparent EC); therefore, calibration of EM38 to generate different depth-wise predictive equations to convert ECa to ECe is required. Various regression equations are reported to convert ECa to ECe (Rhoades et al. 1989a, b; Im-Erb et al. 2005). Soils are heterogeneous, and thus, there is no universal relationship existing between ECe and ECa; in each study area, relationship is to be developed.

The EC value is a combined result of physical and chemical properties of soil. It has potential applications in agriculture for management decisions and the delineation of management zones. For agriculture applications, EC information works best when yields are primarily affected by factors that are best related to EC, for example, water holding capacity, salinity level, and depth of topsoil. As a result, it may

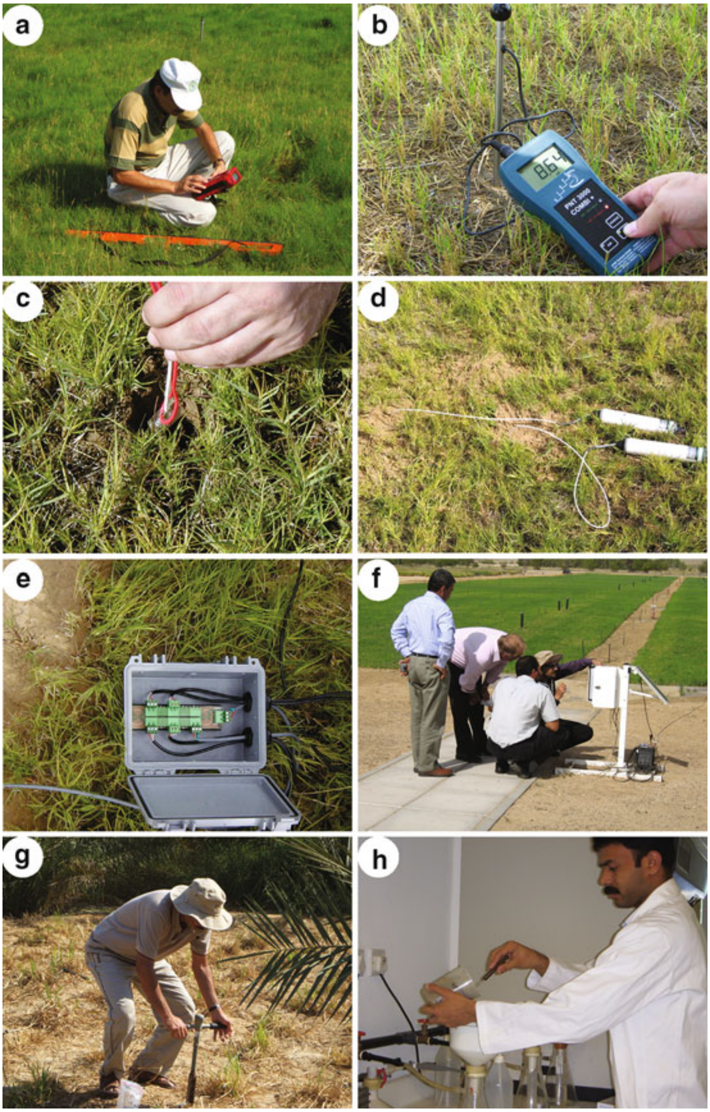

Fig. 1.3 Various views of salinity monitoring in irrigated agriculture field, (**a**) geophysical ECa assessment in a grassfield by EM38 in horizontal mode, (**b**) root zone ECa assessment in a grassfield by salinity probe, (**c**) placing salinity sensors at root zone, (**d**) smart interface connected with salinity sensors in root zone, (**e**) interface connected to databus leading to datalogger, (**f**) instant view of EC on datalogger, (**g**) field sampling for salinity monitoring and, (**h**) soil saturation extract collection in laboratory

not work well in areas when other factors (such as disease and pests) are more predominant. This has to be considered carefully while managing soils from salinity perspectives.

Salinity probes are handy equipment that are easy to use in open field (Fig. 1.3b) and pot experiments manually and give instant apparent salinity information (mS cm^{-1} and g L^{-1}) and avoid conducting soil sampling and preparation. At ICBA we use PNT 3000 COMBI⁺ model that brings together two important functions of salinity measurement: (1) the salinity measurement directly in soils or substrates (activity), taking into consideration the relevant soil properties, like temperature, soil moisture, and soil compaction, and (2) the EC measurement in solutions and suspensions. The PNT COMBI⁺ provides an extended EC-measuring range from 0 to 20 dS m^{-1} and from 20 to 200 dS m^{-1}.

In a recent study at ICBA field station, Shahid et al. (2010) developed correlation between ECa measured by salinity probe and ECe. These correlations provide baseline to convert ECa into ECe; the latter is internationally used to determine salt tolerance of plants.

1.3.3 *Salinity Monitoring Through Real-Time Dynamic Automated Salinity Logging System (RTDASLS)*

This is a modern in situ salinity logging system. Salinity sensors are to be buried at desired root zone depth (Fig. 1.3c) where salinity monitoring is required. A feature of the salinity logging system is that it does not require any knowledge of electronics or computer programming. To operate the salinity station, simply plug in a salinity sensor (Fig. 1.3c), and through smart interface (Fig. 1.3d) and databus (Fig. 1.3e), the Smart Logger (Fig. 1.3f) will then search the databus and automatically identify the number of salinity sensors connected and begin logging them at hourly intervals or any other time interval as programmed. For custom configuration of the Smart Logger or salinity sensors, a simple menu system can be accessed through HyperTerminal that provides complete control over each individual sensor's setup. Instantaneous readings from sensors can be viewed on the logger's display directly in the field without the need for a laptop (Fig. 1.3f). Data can also be accessed in the field by memory stick or remotely using a mobile phone modem. This data is then available for graphing and interpretation in Excel. The RTDASLS has been successfully used in grass field at ICBA field station (Shahid et al. 2008).

1.3.4 *Rational for Saturated Soil Paste Extract EC (ECe)*

The EC of solution extracted from a saturated soil paste (which has water content about double than at field capacity) has been correlated with the response of various crops. This measure, known as electrical conductivity of the soil saturation extract (ECe), is now the generally accepted standard measure of soil salinity even though the procedure is time-consuming and requires vacuum filtration. In order to collect soil extract from saturated paste, soil samples from representative sites are to be collected carefully using standard sampling tools (Fig. 1.3g).

The preparation of saturated soil paste is simple, where about 300 g of sieved <2-mm air-dried soil is used to prepare saturated soil paste. The deionized water (DIW) is gradually added until all the soil is moist, and then they are mixed with a spatula until a smooth paste is obtained. The paste should glisten and just flow when the container is tilted and have no free water on the surface but be in a condition whereby it slides cleanly off the spatula. Soil saturation extract can be obtained under vacuum (Fig. 1.3h) and ECe determined by standard EC meter.

It should be noted that EC measurement on extracts or suspensions of fixed soil: water ratio (commonly 1:1, 1:2.5, or 1:5) does not give a reliable correlation. Such extracts or wider ratio is more convenient where the soil sample is limited. This is because the amount of water held at a given tension varies from soil to soil, depending on texture, the type of clay mineral, and other factors. However, when regular salinity mapping is to be accomplished and results are required on a daily basis, then it is essential to develop relationships between ECe, and EC measured by field scout (salinity probe) and EC measured on different soil: water content suspensions.

1.3.4.1 Correlation Between EC measured by Salinity Probe and EC at Various Soil: Water Contents

For many reasons, laboratory analysis of soil saturation extract is still the most common technique for assessing soil salinity and other potential hazards. Salinity of the saturation extract is considered a standard procedure because the amount of water that a soil holds at saturation (saturation percentage) is related to a number of soil parameters, such as texture, surface area, clay content, and cation-exchange capacity. Lower soil water ratios, for example, (1:1; 1:2; 1:5), make extraction easier but, cautioned, less related to field moisture condition than the saturated paste. The choice of equipment/procedure depends upon the purpose of salinity determination, size of the area being evaluated, the depth of soil to be assessed, the number and frequency of measurements needed, the accuracy required, and the availability of resources. The standard way is salinity monitoring through collecting soil samples from the root zones over a period of time and their analyses in the laboratory on a soil saturation extract.

As a part of ICBA salinity monitoring program, the soil team collected many samples from experimental plots irrigated with different water salinity up to maximum of seawater. These samples were air-dried and processed to collect water extracts from 1:1, 1:2.5, and 1:5 (soil: water) suspensions as well as soil extract from saturated soil paste. In addition, we also measured field conductivity (ECa) in mS cm^{-1} using field scout (Fig. 1.3b). Simple statistical test was used (Table 1.3) to develop correlation and correlation coefficient (R^2) and derived factors to convert EC determined by various water contents and salinity probe (field scout) to ECe (Table 1.4).

The above correlations are developed for fine sand (Soil Survey Division Staff 1993) textural class (sand subfractions: very coarse 3%, coarse 3%, medium 4%,

Table 1.3 Correlation between EC measured by salinity probe vs 1:1, 1:2.5 and 1:5 EC (soil: water) EC with ECe

Correlation equation and coefficient	Definition of x and y
(a) Correlation between EC by field scout and various soil water contents	
$y=2.2936x+4.0177$; $R^2=0.8896$	x = EC by field scout and y = ECe
$y=0.7929x+0.8131$; $R^2=0.9449$	x = EC by field scout and y = EC (1:1)
$y=0.6057x+0.4763$; $R^2=0.9105$	x = EC by field scout and y = EC (1:2.5)
$y=0.4733x+0.3269$; $R^2=0.9023$	x = EC by field scout and y = EC (1:5)
(b) Correlation between EC at different water contents	
$y=0.3276x-0.4152$; $R^2=0.9539$	x = ECe and y = EC (1:1)
$y=0.2642x-0.4782$; $R^2=0.9688$	x = ECe and y = EC (1:2.5)
$y=0.1357x-0.1835$; $R^2=0.9137$	x = ECe and y = EC (1:5)
$y=0.5737x+0.1119$; $R^2=0.9786$	x = EC (1:2.5) and y = EC (1:5)

Table 1.4 Conversion factor for ECe determination from different soil: water ratio and field scout ECe values

EC (different methods) dS m^{-1}	Multiplied by (factor) to get ECe
Field scout (ECa)	ECa × 3.81
EC (1:1)	EC (1:1) × 3.35
EC (1:2.5)	EC (1:2.5) × 4.77
EC (1:5)	EC (1:5) × 7.31

fine 51%, very fine 37%), silt (coarse 0.5%, fine 0.5%), and clay (1%) at ICBA field station. The ICBA soil is very strongly calcareous (50–60% $CaCO_3$ equivalents), and according to US Soil Taxonomy, it is "Typic torripsamments, carbonatic hyperthermic" with saturation percentage (22–26). Different conversion factors may exist in other areas of different soil textures and composition of salts. Therefore, they are site specific and their direct use in other areas with different soils is cautioned. It is recommended to develop similar correlations at local conditions and then use confidently to obtain ECe, a prerequisite for crops growing in saline field for root zone salinity management. Such an initial development is useful; it saves time and provides on-site salinity information and eliminates soil sampling and laboratory analyses.

1.4 Soil Morphology

Soil morphology can be investigated at four levels:

– *Macromorphology* – field level investigation with naked eye
– *Mesomorphology* – when naked eye cannot resolve the details, then it is aided with hand lens or binocular

- *Micromorphology* – when optical aid is needed for the naked eye to resolve details at higher magnifications, for example, in soil thin sections as studied with, a polarizing microscope is considered as an extension to field morphological studies (Cady 1965)
- *Submicroscopic*- the resolution of details at submicroscopic level using electron microscopes (scanning and transmission). Bisdom (1980) coupled the optical microscopy with submicroscopic methods and later with contact microradiography (Drees and Wilding 1982)

1.4.1 Field Assessment (Macromorphology: Naked Eye Salinity Diagnostics)

Macromorphology can be established during field investigation on broader scale, and features of interest can be captured with digital camera (still or video). Such investigations provide rapid information about the area of interest. During a field study of the Abu Dhabi coastline, a number of features were captured showing salt crusts in different morphological forms (hexagonal, circular, pillars, cubic, massive, cracked, etc.); some of the features are shown in Fig. 1.4a–d. In agricultural farms, salinity also exists due to poor management of soil and water resources, for example, drip-irrigated Rhoades grass field in Madinat Zayed, Abu Dhabi (Fig. 1.4e) and furrow-irrigated barley field in Pakistan (Fig. 1.4f).

1.4.2 Mesomophology

Mesomorphological observations are made when naked eye cannot resolve the details of the features of interest. The naked eye is then aided with hand lens or binoculars at lower magnifications. Such observations can be made in the field (hand lens) or in laboratory using binoculars. Examples of such mineral features (nahcolite) from a salt crust developed through simulation in the laboratory are shown in Fig. 1.5a, b.

1.4.3 Micromorphology

Micromorphology – when optical aid is needed for the naked eye to resolve details at higher magnifications, for example, in soil thin sections as studied with, a polarizing microscope is considered as an extension to field morphological studies (Cady 1965). Examples of such observations are thenardite in soil matrix (Fig. 1.4g) in an Aridisol from Punjab, Pakistan, and lublinite calcite coating the voids (Fig. 1.4h) in Aridisols from Pakistan (revealing calcification soil forming process).

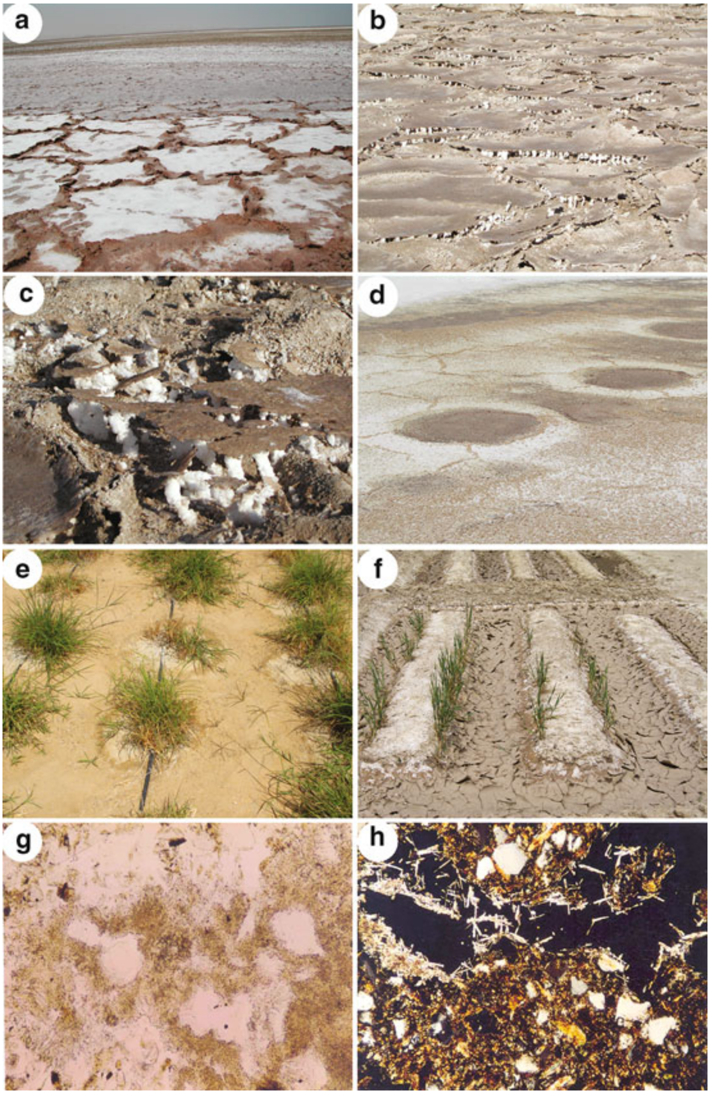

Fig. 1.4 Field observation of soil salinity at macro scale in Abu Dhabi Emirate, (**a**) hexagonal features, (**b–c**) surface cracking and salt pillars lifting surface crust, (**d**) circular salt features, (**e**) salinity in drip-irrigated Rhoades grass field, (**f**) salinity in furrow-irrigated barley field in Punjab Pakistan, (**g**) microscopic observation in thin section (Pakistan) showing thenardite in saline soil matrix, (**h**) lublinite crystals coating void surface (lublinitan), in a saline soil from Pakistan

1.4.4 Submicroscopic Observations by SEM

When morphological resolution of details is required at submicroscopic level, then features are investigated by electron microscopes (scanning and transmission). Bisdom (1980) coupled the optical microscopy with submicroscopic methods and

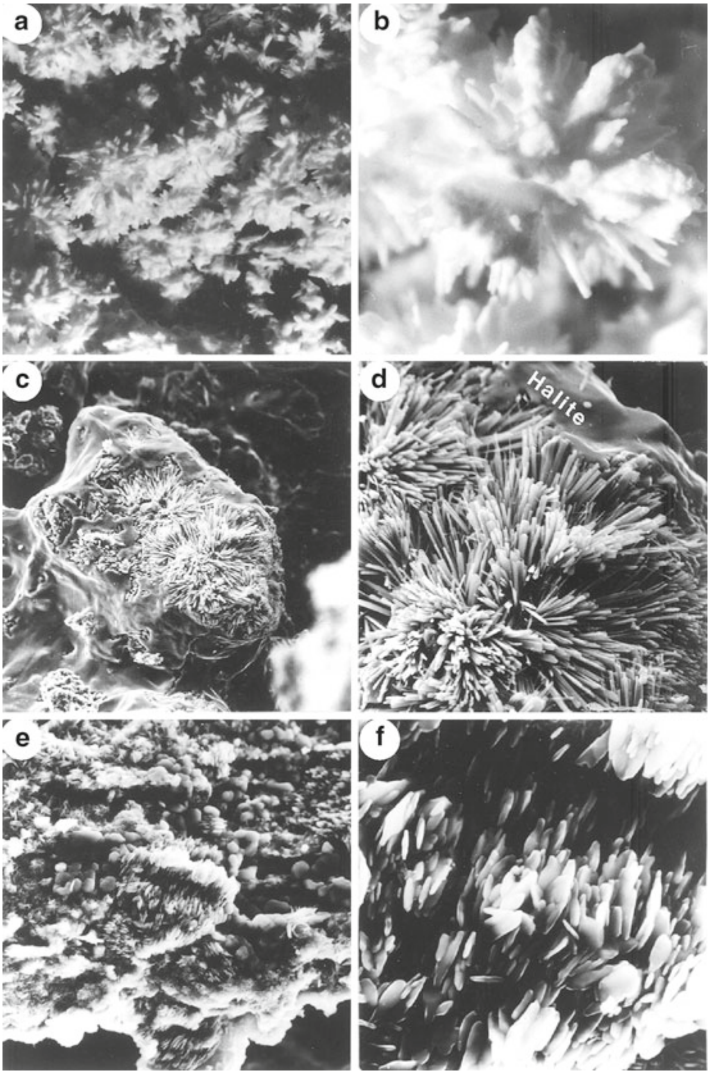

Fig. 1.5 (**a**) The nahcolite ($NaHCO_3$) efflorescence as seen under the binocular (width 1.1 mm), (**b**) selected part from (a) at higher magnification (width 0.28 mm), (**c**) SEM micrographs of lath-shaped glauberite [$Na_2Ca(SO_4)_2$] emerging from massive halite (NaCl) from Playa valley of Spain (width 160 μm), (**d**) glauberite at higher magnification (width 64 μm), (**e**) mixture of platy thenardite (Na_2SO_4), granular halite (NaCl) and lath-shaped trona [$Na_3H(CO_3)_2.2H_2O$] from saline soil Pakistan (width 80 μm), and (**f**) details of platy thenardite (width 16 μm)

later with contact microradiography (Drees and Wilding 1983). These electron microscopes are supplemented with microchemical analyzer (EDXRA, WDXRA), allowing in situ microchemical analyses (nondestructive). To study salt crusts at submicroscopic level, soil samples need coatings with gold-palladium (an alloy), or carbon on salt crusts is needed to make the sample conductor.

Figure 1.5 presents submicroscopic features of salt crust from Playa valley in Spain (Fig. 1.5c, d). The salt crusts were collected by the author during his visit to Spain and studied on SEM. The SEM micrographs (Fig. 1.5c, width 160 μm) show lath-shaped glauberite [$Na_2Ca(SO_4)_2$] emerging from massive halite (NaCl); the details of glauberite at higher magnification can be seen in Fig. 1.5d (width 64 μm). In another feature of a salt crust, mixture of platy thenardite (Na_2SO_4), granular halite, and lath-shaped trona [$Na_3H(CO_3)_2.2H_2O$] from saline soil Pakistan (width 80 μm) is evident (Fig. 1.5e), whereas Fig. 1.5f shows the details of platy thenardite (width 16 μm) at higher magnification. The mineral composition was confirmed using microchemical analyses (EDXRA) and the investigation of same feature with XRD.

1.4.4.1 Transition from 2D to 3D Information

The low-temperature ashing (LTA) is a technique of surface oxidation suitable for selective resin removal from thin sections. Basically, it involves the partial ionization of oxygen at low pressure by high-frequency (radio or microwave) excitation to produce a "nonequilibrium plasma" in which there is an abundance of free electrons accelerated to high velocities equivalent to temperature of several thousand degree centigrade, while the velocity of the abundant excited atoms and molecules is equivalent to temperature of a few hundred degree centigrade only. Such plasma can achieve controlled oxidation and volatilization of organic materials at relatively low temperature, the actual sample surface temperature depending on oxygen flow rate and RF power input but being of the order of 150–120°C (Thomas 1974). The LTA is operated at a frequency of 13.56 MHz and an oxygen flow rate of 200 ml $minute^{-1}$ at a pressure of 1 mm Hg. The power input is kept at its lower value of 150 W; however, it can be increased continuously to 300 W to minimize the temperature elevation and distortion in the sample. A period of 10–15 min was found to be adequate for ashing. The ashed thin section was stuck onto a 1-cm carbon stub using normal araldite and coated with carbon in an evaporator with a layer of 20–30 nm thick to prevent charge buildup on the specimen and to hold the surface of the sample at a constant electro-potential. The Hitachi Instrument Co. model SEM S0520 was operated at an accelerating voltage of 15–25 kv. The ICN low-temperature asher model 302 supplied by the Tracerlab was used to remove the resin from thin section. Prospects of the technique are described by Jenkins (1980) and Price and Jenkins (1980).

In an earlier publication, Price and Jenkins (1980) emphasized the limitations on the use of LTA, showing crystals of gypsum cannot survive the process of LTA. Such damage to gypsum crystals has also been recorded by Frazer and Belcher (1973), thus suggesting the incapability of LTA technique to gypsids. In this context, limited investigations have been made to explore the details of 3D in thin sections because of either partial or complete loss of the section. More specifically these studies reported the loss of gypsum crystals through dehydration and hence show limited or no access to the third dimension.

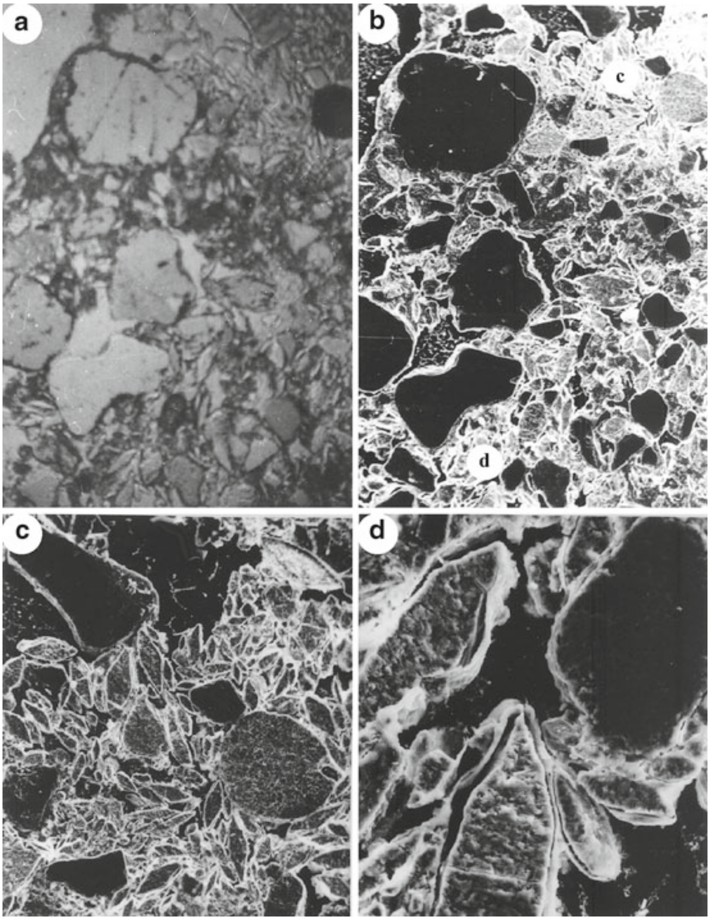

Fig. 1.6 Gypsic soil from Hofuf, Saudi Arabia in thin section showing lenticular gypsum crystals, (**a**) 2D feature under optical microscope (width 1.22 mm), (**b**) same feature as in (a) intact feature after removing resin through low temperature ashing-3D feature, (**c**) details of lenticular crystals revealing the survival after LTA process and showing third dimension (width 0.6 mm), (**d**) etching of lenticular gypsum crystal and coating features over gypsum crystals (width 0.17 mm)

For the last three decades, no further attempts have been made for such studies. In order to bridge the gap in such studies, an investigation was made on soil thin sections from Hofuf, Saudi Arabia (Fig. 1.6). The figure clearly revealed strong promise for 3D investigation in soil thin sections (Fig. 1.6a–d). The study provides evidences for great promise to study thin sections already studied by OM for their further 3D evaluation at the submicroscopic level. The objective of this investigation has been to reassess the technique for gypsids to elucidate if there is any possibility to open the closed chapter again and to study thin section at a submicroscopic level after the LTA process. Shahid (2009) has successfully studied calcids from Pakistan, where needle-shaped calcite (lublinite) has survived the LTA process.

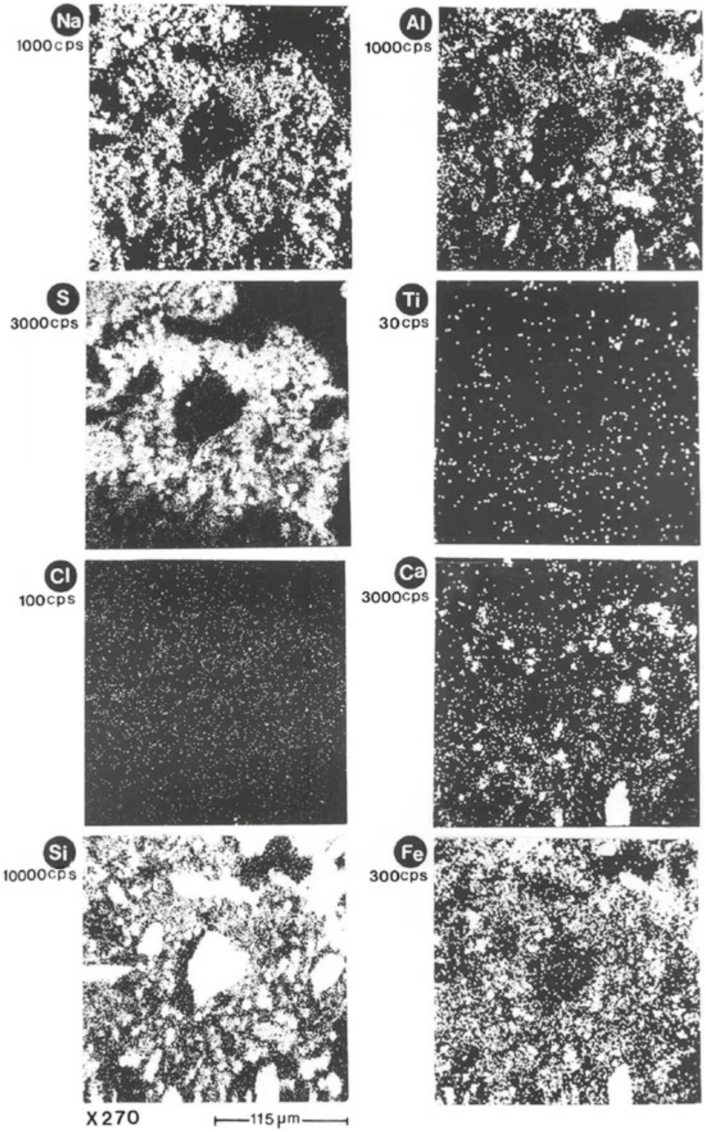

Fig. 1.7 Elemental mapping in a thenardite rich salt crust through Electron Probe Micro Analyses

1.4.5 *Elemental Mapping in Saline Features: EPMA Observations*

The feature (Fig. 1.4g) shows some anhedral crystals embedded in thenardan. These anhedral crystals were initially thought to be of some unknown salt minerals. The x-ray mapping (Fig. 1.7) shows the relative abundance of the Na, S, and Si, where

Na and S mainly exist together, which suggest the presence of thenardite. In the same sample, thenardite and mirabilite ($Na_2SO_4.10H_2O$) have been detected by other complementary techniques such as XRD. The anhedral crystals embedded in the thenardan only revealed presence of Si, which suggests the crystals to be of detrital quartz. It is assumed that these quartz grains are embedded in recrystallized thenardite from the evaporation of Na- and S-rich underground water. The thenardite matrix around the quartz also shows the presence of Si, Al, Ti, Ca, and Fe, suggesting the presence of quartz, feldspar, calcite, phyllosilicates, and small amounts rutile/brookite. The EPMA beam was also focused on the features where halite was expected, but this damaged the feature (destructive technique for halite analysis by EPMA) and the composition could not be revealed.

1.5 Conclusions and Recommendations

This chapter presents a comprehensive review of literature on soil salinity assessment technologies to aid measurements from regional, national, farm, to submicroscopic levels of investigation. The user can select the technique best suited to objective and availability of resources. When selecting the technology for a specific purpose, it is important to consider pros and cons of each technique. Integration of techniques can provide better salinity status and help future prediction to allow taking necessary action. RS imagery and GIS are great techniques for salinity mapping at small scales. In areas where saline-brackish water is used for irrigation purpose, farm-based salinity mapping and monitoring tools such as electromagnetic induction (EMI) equipment EM38 and salinity probes are recommended to understand day-to-day salinity status to manage soils for better agricultural production. For rapid salinity survey by EM38 and field scout, it is recommended to develop site-specific relations between EC measured by various techniques to obtain the standard salinity values of the ECe. Salinity modeling can provide important information; however, they require data which in many developing countries are not easy to produce. Elemental mapping through submicroscopic investigation can provide in situ salinity status and behavior in actual soil environment; however, such studies are mainly of academic interest and directly do not provide handy information for the farmers for salinity management. Innovative work on the study of thin section for 3D investigation by SEM provided opportunity for soil micromorphologists to study same features initially studied on the optical microscope for 2D information to be further studied by SEM for 3D information at submicroscopic level.

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