1 Introduction

1.1 Problems of Soil and Groundwater Salinization in the Khorat Plateau

The Khorat Plateau is located in the northeastern Thailand where covers about 1/3 of the whole area of the country or about 170 230 km^2. It is divided by the Phu Phan Range into two depositional basins, the Sakon Nakhon Basin in the north and the Khorat Basin in the south (Figure 1.1). It continues to experience severe problems of saline soils and saline water caused by the rock salt in the Maha Sarakham Formation and some salt contained in the Upper Clastic Member and also in the Plio-Pleistocene Formation (Wongsomsak, 1986). Survey data from the last 10 years estimated that salt-affected areas in Northeast Thailand occupy about 28 400 km^2 or 17 percent of the region (Arunin, 1992). The salinization processes are believed to be activated both by natural and man-made activities. Water in several groundwater wells tastes salty and several natural and man-made lakes and ponds contain salt water. These problems affect the living conditions of the people in the Khorat Plateau and the economy of the region.

Rock salt in the Maha Sarakham Formation, which is believed to be the main cause of salinization, has been found in both the Sakon Nakhon and the Khorat Basins. The study of more than a hundred boreholes drilled through the rock salt of the Maha Sarakham Formation in various places in the Khorat Plateau shows that the thickness and depths to the rock salt range from a few meters to hundreds of meters (Suwanich, 1994). These rock salt layers are believed to be deposited in these two basins more than 65 million years ago, which where later filled with other sediments (Sattayaruk, 1985). Where the Maha Sarakham rock salt is deeply buried, it becomes mobilized and may flow upwards to form salt domes and anticlinal structures. It may also be deformed into discordant bodies, lubricating and filling in surrounding gaps, and drag adjacent strata (Warren, 1999). And according to the study of Japakasetr (1985), correlating rock salt from one borehole to another is difficult. Thus, the subsurface geology of the Khorat and Sakon Nakhon basins appears to be very complex and up to now no study could clearly explain the way the salt found its way to the surface.

Therefore, the abundance of saline soil and saline water needs a careful and intensive study to find out how the salinization spread, what are the main causes of the salinization, and what are the probable mechanisms of salinization both on local and regional scales. An assessment of the environmental impacts caused by the rock salt in the Maha Sarakham Formation as well as salinity control and management is needed in order to mitigate harmful impacts on the economy and the ecosystem.

1.2 Objectives of the Study

The subject of this study is an integrated interpretation of remote sensing data, data provided by geophysical exploration methods, and data provided by other data bases. The goals of the study are as follows:

1. To map the distribution of saline soils in the Khorat Plateau with remotely sensed data;

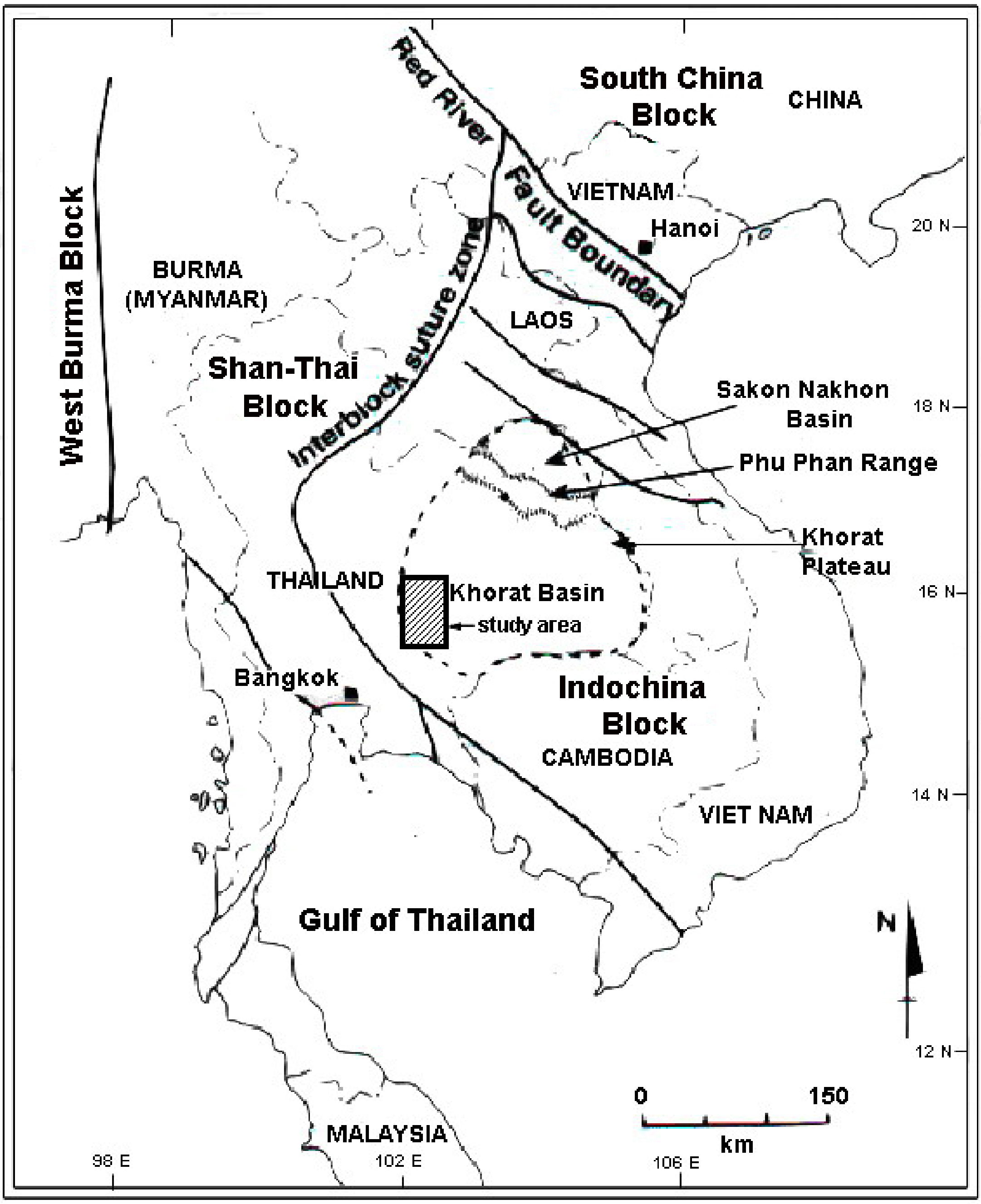

Figure 1.1 Location of the study area and tectonic setting of the Khorat Plateau, the Khorat basin and the Sakhon Nakhon basin (modified after Mouret, 1994).

2. To correlate presumably salt-related features visible in the remote sensing data with information/indications provided by geophysics or other sources of data;
3. To develop tentative assumptions on the relationship between typical salt-related features in the remote sensing imagery and likely corresponding subsurface conditions (depth and subsurface morphology of the rock salt surface, role of lineaments, etc.);
4. To outline tentative concepts on the development of soil salinity, depending on lithological and structural conditions, and considering effects of deforestation.

1.3 The Study Area

The study area is located in the western part of the Khorat Basin, the Khorat Plateau, in northeastern Thailand. This region is politically divided into 18 Provinces (Figure 1.2). The topography of the Northeastern Thailand in general consists of rolling plains bounded by mountains to the west and south. The whole area slopes gently toward the Mekong River. The Plateau extends northward and eastward across the Mekong River into Laos.

The study area is bounded by longitudes 101°30' and 102°30' E, and latitudes 14°45' and 16°00' N (Figure 1.1) and covers an area about 13 200 km^2. It can be easily reached by Highway No.2 and many of local roads in all seasons (Figure 1.3). The dominant landforms in the study area consist of the two main types: undulating plains bounded by broad crests with gentle straight slopes of 20 – 30 m relief and flood plains. Undulating plains are common on the higher ground away from river banks. They are characterized by small depressions interspersed with numerous low hills. This landscape is developed not only by weathering processes and river erosion, but also by the action of groundwater, which dissolves the rock salt in the subsurface. Floodplains are limited in extent, found and formed mainly in the lower parts of the river basins and there are numerous ponds and lakes of various sizes scattered all over the study area (Figure 1.4). Two main river courses run through the study area: Mae Nam Chi River to the north and Mae Nam Mun River to the south (Figure 1.5). Fine-dendritic and deranged drainage patterns dominate the study area.

The entire area is located in the tropical zone, influenced by monsoons from three directions: NE, SW and W, and by winds from the south. The direction of monsoons and winds changes circularly during the year. The rainfall, and thus the season, depends on the wind direction. Accordingly three seasons are distinguished: winter, summer and rainy season.

The winter season lasts from November to February when the NE monsoon moves southward from China to Thailand, carrying dry cool air. This causes a decrease of the temperatures and the minimum temperature can drop to an average of 10° C. Summer season starts in March or April and lasts to the beginning of May. The average temperature can rise to 40° C, and reaches its highest values in mid April. Thunder storms occur when the cool air from the NE confronts the warm south wind. The rainy season lasts from end of May to October, when West and South-West monsoons coming from the South China Sea blow over the area. The average rainfall is around 1 051 mm/yr.

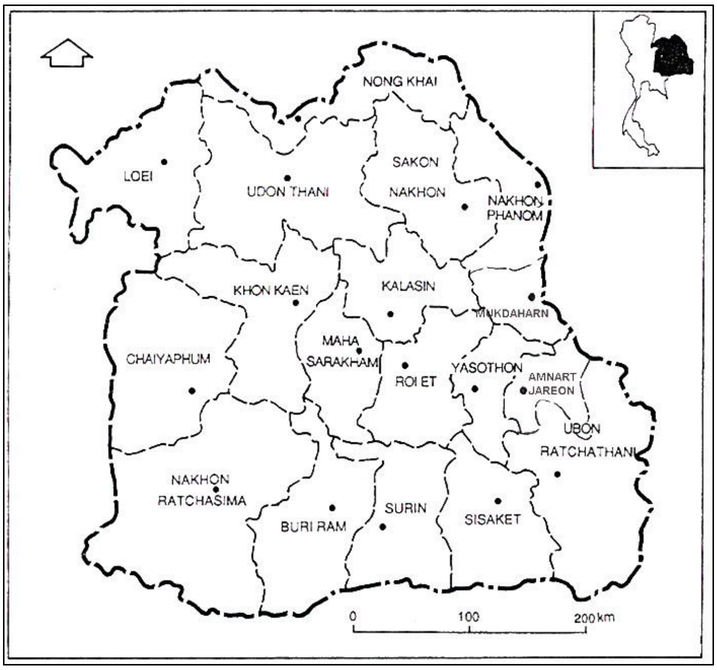

Figure 1.2 Administrative map of northeast Thailand.

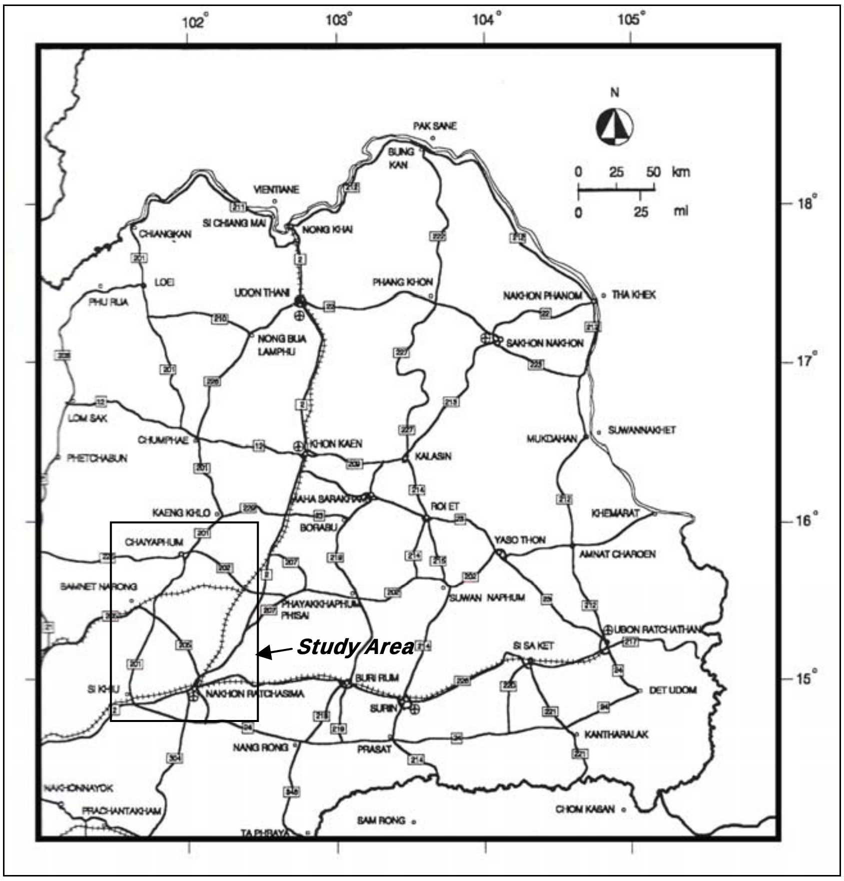

Figure 1.3 Transportation network in Northeastern Thailand (highways, main roads, railways and airports).

The average rainfall in the Khorat Plateau is not much lower than in other parts of the country, but the evaporation is very high, reaching around 1 750 mm/yr (Nakhon Ratchasima station, 1991-2000). In this area most times of the year evaporation is higher than rainfall, so that all of the rainfall is consumed by evaporation, except during August and September when evaporation is slightly lower than rainfall.

The cultivation in the study area is divided into two types according to the geographic conditions as flood plain/ broad valley and upland crop area. Paddies and mixed orchards are the two main types cultivated in flood plains and broad valleys, while cash crops, e.g. cassava and sugar cane are mainly planted together with few plantation forests of eucalyptus on the elevated areas. During the wet season farmers normally plant rainfed rice, while during the dry season they plant cassava, kenaf, watermelon, tobacco, or leave the ground fallow. With irrigation water, farmers grow rice, sweet corn, soybeans, peanuts and tomatoes. Land use in the study area is mainly agricultural with paddy fields and cash crops and will be discussed in detail in chapter 4.

Figure 1.4 Topographic map showing boundaries of the study area (within red rectangle) covering longitudes 101°30’ and 102°30’ E, and latitudes 14°45’ and 16°00’ N.

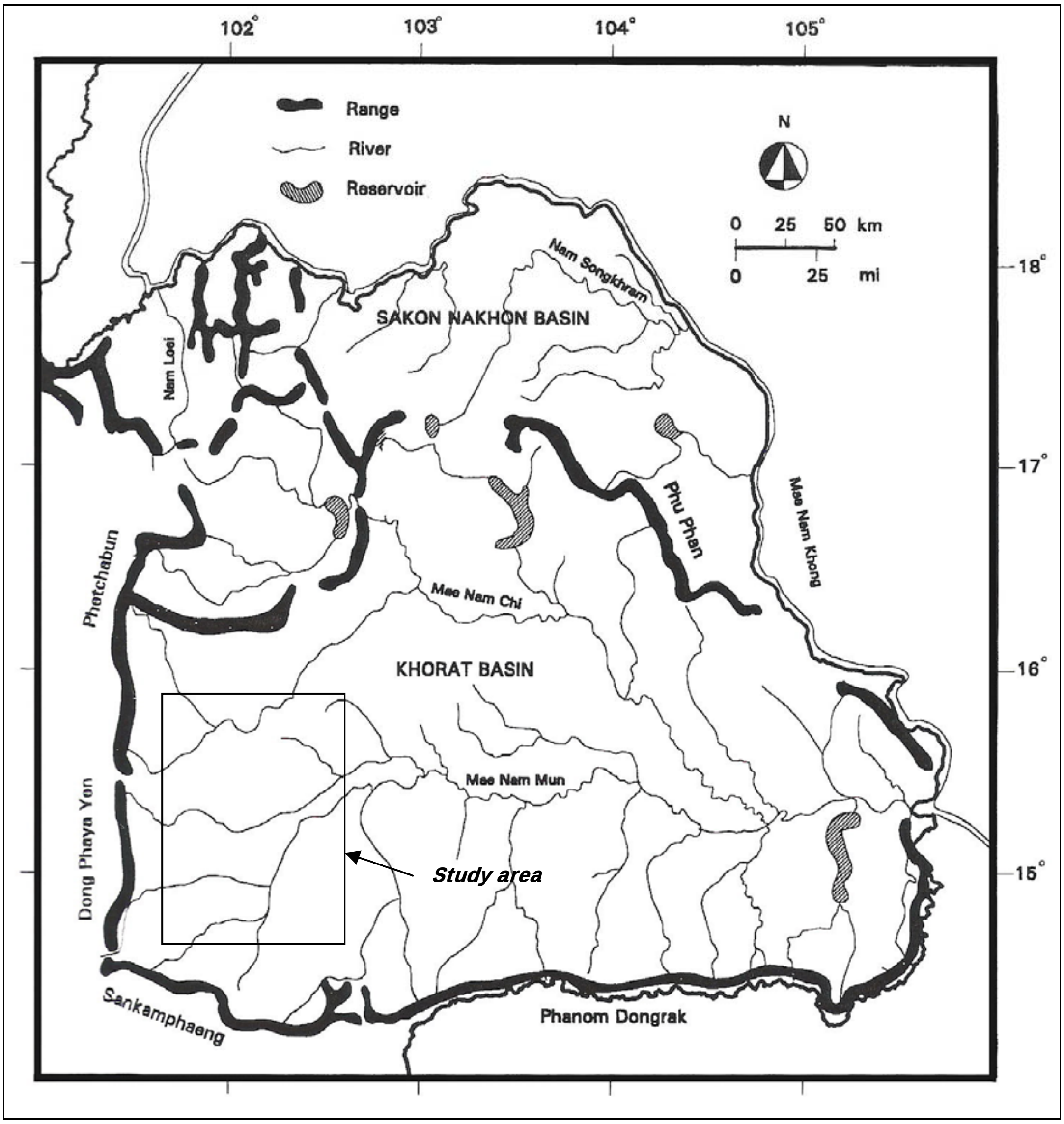

Figure 1.5 Major geographic elements in Northeastern Thailand (modified after Chulalongkorn, 1991).

1.4 Previous Work

1.4.1 Geological Studies

A reconnaissance geological survey of the Khorat region was first conducted by Lee *et al*. in 1921. A combined team of geologists from the Thai Geological Survey and the US Geological Survey collected considerable information on the Khorat Plateau in their geological reconnaissance of the mineral deposits of Thailand (Brown *et al*., 1951). Subsequent investigations focused first on the water supply problems of the region. The ground water system is described by La Moreaux (1959), Howorth *et al*. (1965), Piancharoen (1973 and 1982), Ramnarong (1985), Wongsawat (1985) & Ghassemi *et al*. (1995).

The stratigraphy of the region began to be studied in detail by Jalichan *et al*. (in La Moreaux *et al*., 1959), and was refined by Ward & Bunnag (1964), Bunopas (1983) and Piyasin (1995).

General geology was discussed in papers by Hite (1973), Hahn (1982), Satayarak (1985), Cooper *et al*. (1989), Sessler (1990), Haggemann (1994) & Mouret (1994). Following reconnaissance geological mapping of the Khorat Plateau by Union Oil geologists (Borax & Stewart, 1965), detailed geological mapping was carried out by the Geological Survey Division of the Department of Mineral Resources, mainly during the 1970’s, reviewed again in the year 1999, and published at a scale of 1: 2,500,000.

Palaeontological studies in the Khorat region began in the earliest in the 1960’s with co-operation from Japan (e.g. Kobayashi *et al*., 1964; Iwai *et al*., 1968). More recently, palaeontological interest has focused on vertebrate fossils in the Mesozoic, particularly on dinosaurs (e.g. Buffetaut & Ingawat, 1983; Suteethorn *et al*., 1990; Buffetaut *et al*., 1997), and the biostratigraphy of Palaeozoic invertebrate faunas (e.g. Fontaine *et al*., 1996).

Salt resources and its related issues were studied by Gardner *et al.* (1967), Hite (1973), Sinanuwong & Takaya (1974A and 1974B), Japakasetr (1977), Japakasetr & Workman (1981), Hite & Japakasetr (1979), Löffler *et al.* (1984), Löffler & Kubiniok (1988), Furukawa & Pichai (1989), Sattayarak & Polachan (1990), Suwanapol (1992), Gronfeld & Buppapong (1992), Tabakh *et al*. (1995) & Utha-aroon *et al*. (1993), respectively.

1.4.2 Soil and Groundwater Salinity

Soils and land use is subjected of publications by Moormann *et al*. (1964), Sonsuk & Hastings (1984), Wongsomsak (1986), Furukawa & Pichai (1989), Kubiniok (1990), & Perry (1996).

Soil salinity was studied by Sinanuwong & Takaya (1974), Sinanuwong *et al.* (1980), Rimwanich & Seubsiri (1984), Takaya *et al.* (1984), Arunin (1984, 1987, 1991, 1992a), Limpinuntana & Arunin (1986), Arunin *et al.* (1988). Groundwater salinity in the Khorat Plateau was studied by Williamson *et al.* (1989), Buaphan *et al.* (1990), Arunin (1984), Tasker (1990) & Srisuk *et al*. (1994, 1995 and 1996).

1.4.3 Remote Sensing

There were many attempts to apply and utilize remote sensing to detect and monitor salt-affected areas. Most of the remote sensing applications to detect and monitor the salt-affected areas were worked out in the past thirty years, and utilized Landsat data such as the work of Dwivedi (1969), Chaturvedi *et al*. (1983), Menenti, Lorkeers & Vissers (1986), Mulders & Epema (1986), Sharma & Bhargava (1988), Singh & Srivastav (1990), Saha, Kudart, & Bahn (1990), Rao *et al*. (1991), Brena *et al.* (1995), & Naseri (1998), respectively.

For ASTER data, Fouad (2003) applied ASTER bands 3, 4 and 5 in terms of a salinity index together with a biophysical method based on detecting the crop reaction to soil salinity via osmotic forces and the increasing surface resistance due to stomatal closure to detect salinity in the irrigated area in the northern part of Syria.

In Thailand, remote sensing technology was first adopted and used for military and land use mapping and later on for natural resources exploitation purposes. These techniques were applied using Landsat data to generate, classify and map saline soil in the northeastern Thailand by the Land Development Department (LDD) in 1975, later revised in 1981 and 1989, and further in the work of Sinanuwong *et al.* (1980), Arunin *et al.* (1981) and (1984), Limpinuntana & Arunin (1986), Eiumnoh *et al.* (1994), Sukchan *et al.* (2000), & Khundee (2003), respectively.

A more recent study was conducted in the framework of the Thai-German Technical Cooperation Project “Environmental Geology for Regional Planning” run by the Federal Institute for Geosciences and Natural Resources of Germany (BGR) and the Department of Mineral Resources of Thailand (DMR). This study covered selected saline soils, which are typical for major parts of the Khorat Plateau, and aimed to study its development, its expansion and the causes for soil salinization by using remote sensing techniques and other geological methods.

1.5 Data and Equipment

Remote sensing data and computer-based remote sensing working places are available at the Freie Universität Berlin (FUB), German Federal Institute for Geosciences and Natural Resources (BGR), and at the Department of Mineral Resources (DMR), Thailand. BGR, branch Berlin Spandau, also provides a spectrometer, Mark V, for measuring the reflectance spectra of saline soil samples collected from the study area. The Suranaree University of Technology (SUT) in Nakhon Ratchasima provided the geophysical data required and also the instruments for geophysical investigation and processing. Other GIS data, e.g. topographic maps, land use maps, groundwater quality data, geological maps, etc. were supplied by DMR and SUT.

1.5.1 Remotely Sensed Data

Remotely sensed data used in this study were:

1. Landsat 5 (TM) and Landsat 7 (ETM+) data;
2. ASTER data;
3. SRTM (Shuttle Radar Topography Mission) data;
4. Reflectance spectra of saline soil samples of the study area.

1.5.2 Other Data

Additional data employed in this study were:

1. Elevation data, available both in digital format as DEM (Digital Elevation Model) and hard copy of topographic maps covering the whole study area at the scale of 1: 50 000;
2. Soil data;
3. Saline soil maps;
4. Groundwater data;
5. Geological maps at the scale of 1: 250 000 and 1 : 2 500 000;
6. Geophysical data, including seismic reflection data, Vertical Electrical Sounding data (VES), and Microgravity data;
7. Potash and rock salt borehole data;
8. Meteorological data.

1.5.3 Computer Software and Other Equipment

Computer software for satellite image processing employed in this study included:

- ENVI Version 3.4 to 4.1
- Geometica Version 8.2
- eCognition Version 2.2
- ArcView Version 3.2

Equipment for the geophysical investigation included:

- IRIS instrument for conducting the electrical investigation
- OYO Geospace DAS-1, 24-channel and receivers together with 50 kg elastic wave generator
- Garmin 12XL, a GPS device
- Seistrix V.3.4 seismic reflection processing software

1.6 Methods of Investigation

1.6.1 Laboratory Methods

For the purposes of saline area mapping and structural geology study, satellite images of Landsat 5, Landsat 7, and ASTER covering the study area were used. The selected images were digitally processed, and several enhancement techniques were applied for improvement of geologic discrimination and structural mapping, e.g. rock boundaries, lineaments, drainage patterns, etc. The image processing procedures with substantial results were applied to the data covering the whole study area and used as a basis for image interpretation, with additional information also from images obtained from other enhancement techniques. Hard copy outputs from the HP DesignJet 5000 printer were obtained at a scale of 1:100 000 for visual geologic interpretation.

Topographic data, existing land use maps and saline soil maps of the Land Development Department (LDD), groundwater data, geographical data, borehole data and other substantial data were digitized and integrated in order to map the area covered by saline soil and correlated features associated with the subsurface conditions to produce a new land use map and a GIS database of the study area.

1.6.2 Field Methods

Field checking was an essential component of this study. Field work has to be conducted since remote sensing provides information that may be ambiguous.

Two field trips to the study area with a total of 70 days were conducted between October 15 – December 15, 2003, and January 21 – January 30, 2005. Geocoded and processed images at a scale of 1:50 000 and 1:100 000 were used as base maps in addition to topographic maps at the scale of 1:50 000. Field observation sites were recorded using a Global Positioning System (GPS) receiver (Garmin 12 XL). The aim of the field check was to compare typical features that were identified in the images with the in-situ character of rocks and soils, vegetation, geomorphology, land use and others. This way, interpretation results could be verified or modified.

Geophysical investigations were conducted to investigate subsurface geology, and to obtain information on subsurface structures and stratigraphic sequences of salt and the Upper Clastic rocks of the study area. To reach these objectives, seismic, resistivity and gravity survey were used in this study.

Seismic surveys involve analysis of refracted and reflected arrivals that depend primarily on the wave propagation velocity of the earth’s materials. The seismic reflection survey was achieved by gathering and introducing seismic waves into the ground. A portion of the reflected waves returns back to the surface when the conditions of reflected waves are met. The returned waves are recorded by receivers laid out on the surface. Two seismic reflection investigations were conducted by the author in the study area to acquire data for evaluating the depth to the uppermost rock salt layer. The first investigation was conducted at Ban Sida Village, Khong District, Nakhon Ratchasima Porvince, located in the northeastern part of the study area, during May to June, 2001. The second investigation was conducted at Ban Basiew Village, Chaiyaphum Province, located in northern part of the study area, during November 11, 2004 to January 20, 2005, and was budgeted by the BGR. This study also adopted and used the seismic survey data of the Thai-German Technical Cooperation Project “Environmental Geology for Regional Planning” that took place in Dan Khun Thot District, located in the western part of the study area, during April, 2002.

Resistivity surveys measures apparent resistivity of the earth’s materials as a function of depth. The apparent resistivity of soils and rocks is governed by mineral composition, porosity, permeability, and ionic content of pore fluids. Conducting resistivity surveys, currents are sent into the ground through a pair of electrodes and the potential difference is measured between a pair of potential electrodes. The apparent resistivity is the bulk resistivity of rocks and soils that the current passes through. This study employed the Vertical Electrical Sounding method for detecting the apparent resistivity of the subsurface materials of the study area. The Schlumberger configuration was used for this investigation with the maximum of 1 kilometer between the electrical poles distance. This resistivity survey was conducted at Ban Sida Village site suddenly after the seismic survey had been completed in

2001. Moreover, the resistivity data of the Dan Khun Thot Project was also adopted and utilized in this study.

A gravity survey measures properties of the subsurface rocks on the basis of variations in the Earth's gravitational field generated by differences of density between subsurface rocks. The main reason of rock density variation is its composition and porosity. Density increases with depth due to compaction and progressive cementation. Porosity is one of the main controls of density variation in sedimentary rocks. The gravity data adopted and used in this study come from the gravity survey conducted at Ban Sida Village Project in June, 2001.

Information from field work, data visualization, satellite images processing and interpretation, and GIS database were then merged and analyzed to produce the saline soil classification map at a scale of 1:200 000 of the study area, and the conceptual models to clarify the relationship between the area covered by saline soils and their related subsurface conditions.