3 Soil and Groundwater Salinization in the Khorat Plateau

3.1 Soil and Groundwater Salinity

There are extensive areas of salt-affected soils area on all the continents, but their extent and distribution have not been studied in detail (FAO, 1988). Statistics relating to the extent of salt-affected areas vary according to authors, but estimates are in general close to 1 billion ha, which is about 7 percent of the earth's continental extent. In addition to these naturally salt-affected areas, about 77 million ha have been salinized as a consequence of human activities, and 58 percent of these areas concentrated in irrigated areas (Ghassemi, Jackman & Nix, 1995). Major parts of the salt-affected areas are placed in Australia (357.3 million ha), North and central Asia (211.7 million ha) and South America (129.2 million ha) (see Table 3.1). In Southeast Asia, salt-affected areas cover about 20 million ha or about 2 percent of all salt-affected areas of all the continents.

Soil salinity refers to the state of accumulation of soluble salts in the soil. Soil salinity can be determined by measuring the electrical conductivity of a solution extracted from a water-saturated soil paste. The electric conductivity as EC_e (Electrical Conductivity of the extract) with units of decisiemens per meter ($dS.m^{-1}$) or milliohms per centimeter ($mohms.cm^{-1}$) is an expression for the anions and cations in the soil. For the purpose of definition, and from the agriculture point of view, saline soil is classified as shown in Table 3.2. In general, saline soil is a soil that has an EC_e more than 2 $dS.m^{-1}$ at 25^oC (Richards, 1954).

Water salinity is defined by its chemical constituents, and Total Dissolved Solid contents (TDS, mg/l). In natural water, salts are chemical compounds comprised of anion such as carbonates, chlorides, sulfates, and nitrates (primarily in the groundwater), and cations such as potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na). Saline water is a water that has a TDS content more than 10 000 mg/l according to water type classification of Freeze & Cheery (1979) as shown in Table 3.3.

Saline soils may theoretically occur in any region and every climate in the world. However, these soils are mostly concentrated in semi-arid and arid regions. One of the conditions for the presence or formation of saline soils is an evaporation, which greatly exceeds precipitation.

Soil salinization in northeast Thailand is not a new problem and is not entirely induced by human activities. Soil salinization in this region is at least partly a natural phenomenon. There is also archaeological evidence that localized occurrences of surface salt have been utilized for salt making for 2 000 years nearly the same way as it is practiced today (Löffler & Kubiniok, 1988).

The salt-affected soils in the northeastern Thailand are generally sandy, low in fertility and high in sodium and chloride content. Survey data from the last ten years estimated that salt-affected areas in northeast Thailand occupy about 28 400 km^2 or about 17 percent of the land in this region (Arunin, 1992). In this region, a visual assessment of saline conditions includes both the presence of salt- tolerant indicator shrubs such as *Nham Daeng, Nham Phung Dor, Nham Phrom* and *Nham Pee* and salt-tolerant grass as *Sakae*, and also the absence of productive plants such as rice and maize that are unable to tolerate saline conditions. Salt crystals combined with a high soil water content near the surface also provide additional visual indicators of saline land.

Table 3.1 Extent of salt-affected soils on all the continents (Szabolcs, 1979)

Region	**Million of hectares**	**Salt-affected areas (percent)**
Australia	357.3	37.5
North and Central Asia	211.7	22.2
South America	129.2	13.6
South Asia	84.8	8.9
Africa	80.5	8.5
Europe	50.8	5.3
Southeast Asia	20.0	2.1
North America	15.7	1.6
Mexico and Central America	2.0	0.2
Total	952.0	100.0

Table 3.2 General ranges for plant tolerance to soil salinity (Richards, 1954)

Salinity (ECe, $dS.m^{-1}$)	**Saline Level**	**Plant response**
0 to 2	Non saline	Mostly negligible
2 to 4	Slightly saline	Growth of sensitive plants may be restricted
4 to 8	Moderate saline	Growth of many plants is restricted
8 to 16	High saline	Only tolerant plants grow satisfactorily
> 16	Extreme saline	Only a few, very tolerant plants grow satisfactorily

Table 3.3 Water type classification (Freeze & Cheery, 1979)

Water type	**Total Dissolved Solid contents (TDS, mg/l)**
Fresh water	0 to 1 000
Brackish water	1 000 to 10 000
Saline water	10 000 to 100 000
Brine water	> 100 000

During dry season, November to April, the evaporation mostly exceeds the precipitation, the region suffers from a soil moisture deficit, and soil salinity is most widespread. Arunin (1992) reported that about 75 percent of the salt-affected lands in this region are under rainfed rice cultivation and 15 percent are regarded as wasteland. The northeastern Thailand has approximately 7 percent of irrigated area and about 10 percent of these areas are salt-affected. The salt-affected areas have been expanding mainly due to human activities such as deforestation, salt making, irrigation and construction of reservoirs, canals and roads (Wada *et al*., 1994). That implies that inadequate management of agricultural land use accelerates salt accumulation.

Because of the widespread salinity problem in the Khorat Plateau, many researches activities have been undertaken to explain the causes of the problem, and to estimate its extent and to plan its management. The following is a brief description of some of these research efforts.

Sinanuwong *et al.* (1980) described the application of Landsat imagery of July 1975 and 1976, coupled with ground check sampling in about 2 000 km^2 of the Nakhon Ratchasima Province. The soil salinity classes were arbitrarily divided into areas of non-, slightly, moderately and strongly salt-affected, based on the interpretation of the imagery. A field survey was conducted to verify the results of the interpretation corresponding to the time of the year when the images used were taken. Soil samples were taken at the surface and subsurface. The authors also presented the results of their investigations for 14 soil profiles in tabulated form and in form of the soil salinity classes for the study area.

Wichaidit (1983) described and classified the soil salinity of northeast Thailand based on visual Landsat imagery interpretation coupled with field investigations to observe salt crust percentage on soil surfaces in the dry season. His results are shown in Table 3.4.

Table 3.4 Soil salinity level based on salt encrust observed at surface (Wichaidit, 1983)

Salt crust percentage observable on surface	**Soil salinity level**	**Coverage area (km^2)**
No salt crust	Non-saline soil area (High terrace area)	107 840
<1	Potentially saline soil area (elevated areas containing salt-bearing layer in subsoil)	31 040
1 to 10	Slightly salt-affected lowland area	20 160
10 to 50	Moderately salt-affected lowland area	5 920
>50	Severely salt-affected lowland area	2 400
Total		167 360

Rimwanich & Suebsiri (1984) described the nature and management of problem soils in Thailand, which include saline soils, and provide a soil salinity distribution map of northeast Thailand (Figure 3.1).

The Land Development Department (LDD), Thailand, (1995) reported the salt-affected areas in the northeastern Thailand in the provincial level as shown in Table 3.5.

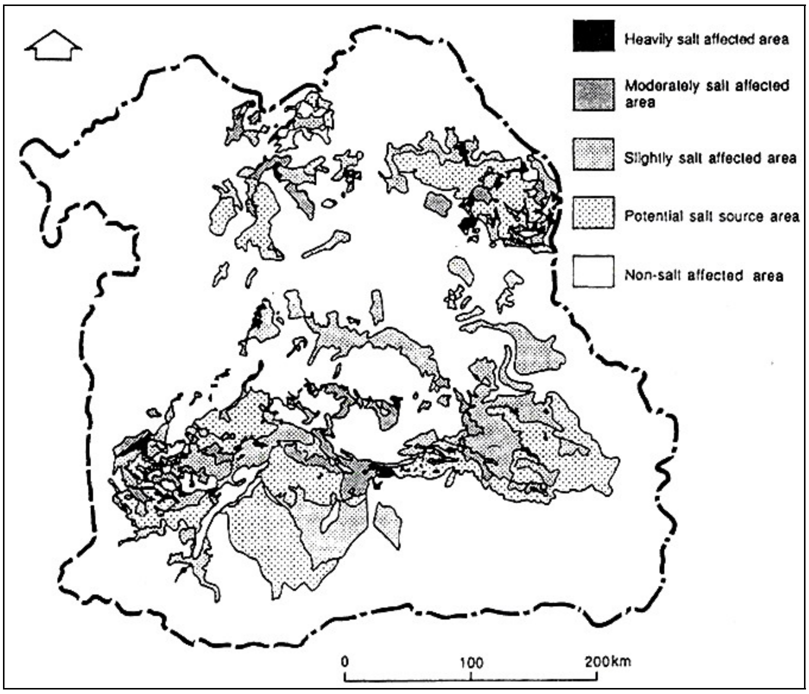

Figure 3.1 Soil salinity distribution in northeast Thailand (after Rimwanich & Suebsiri, 1984)

Table 3.5 Salt-affected areas in the northeastern Thailand in provincial level (LDD, Thailand, 1995)

Province	Salinity Level (km^2)		
	Severely salt-affected area	Moderately salt-affected area	Slightly salt-affected area
Nakhon Ratchasima	760	1 037	2 246
Maha Sarakham	269	366	1 808
Nakhon Phanom	256	602	1 550
Sakon Nakhon	204	157	1 363
Khon Kaen	146	192	816
Nong Khai	141	210	242
Roi Et	129	1 059	1 804
Amnart Jareon	108	19	1 547
Mukdaharn	-	-	-
Ubon Ratchathani	-	-	-
Chaiyaphum	102	299	627
Nong Bua Lampu	86	793	1 615
Udon Thani	-	-	-
Buriram	86	722	2 327
Surin	62	70	661
Yasothon	8	126	2 337
Sisaket	5	210	159
Kalasin	1	44	1 146
Total	2 363	5 905	20 249

3.2 Hydrogeology

Hydrogeology study in this study consists of the study of the meteorological and the groundwater conditions of the study area. Because the groundwater plays the important roles to soil and water salinity, hydrogeology study was an important task of this study. The main aims of the hydrogeology study are to

- characterize the groundwater system,
- assess groundwater quality,
- estimate the impact of land use changes on groundwater recharge and evapotranspiration, and
- to understand the relationship between land use changes and groundwater and salinity problems in the study area.

3.2.1 Meteorological Conditions of the Study Area

The study area is located in the tropical zone, influenced by monsoons from three directions: NE, SW and W, and by wind from the south. The direction of monsoons and winds changes circularly during the year (Table 3.6). The rainfall, and thus the season, depends on the wind direction. Therefore, three seasons are distinguished as winter, summer and rainy season.

The winter season lasts from November to February, when the NE Monsoon prevails in the area. The monsoon, carrying dry cool air, moves southward from China to Thailand. This causes a decrease of the average temperature and the minimum temperature can drop to 10° C in this season (Figure 3.2).

Summer season starts in March or April. In this period there is a gap of monsoons. The area is warmed up by southerly winds. The temperature can rise to 40° C. The highest temperatures are reached in April, afterwards they are decline. Thunder storms occur when the cool air from the NE confronts the warm south wind.

The rainy season lasts from 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 3.3) with two peaks: one in May, the other in August to September.

Table 3.6 Wind directions prevailing in the study area (Margane & Tatong, 2004).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1991	NE	NE	S	NE	S	SW	SW	SW	W	NE	NE	NE
1992	NE	S	S	S	S	SW	SW	W	W	NE	NE	NE
1993	NE	NE	S	S	S	SW	W	SW	W	NE	NE	NE
1994	NE	NE	NE	S	SW	SW	SW	SW	W	NE	NE	NE
1995	NE	NE	S,NE	S	SW,S	S	W	SW	NE	NE	NE	NE
1996	NE	NE	S	S,NE	SW	SW,S	SW	SW	SW	NE	NE	NE
1997	NE	NE	NE	S	S	SW	SW	SW	W	NE	NE	NE
1998	NE	NE	S	S	S	SW	S	W	NE	NE	NE	NE
1999	NE	NE	S	E	SW	SW	SW	SW	SW	E	NE	NE
2000	NE	NE	NE	S	SW	SW	W	W	W	NE	NE	-
sum	NE	NE,S	S,NE	S,NE,E	S,SW	SW,S	SW,W,S	SW,W	W,NE,SW	NE	NE	NE

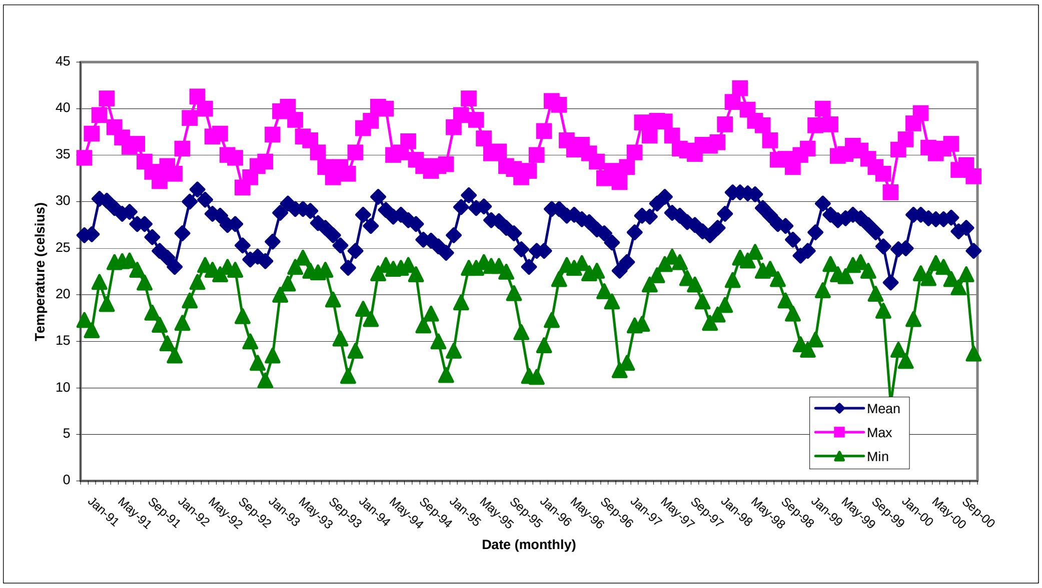

Figure 3.2 Monthly temperature at Nakhon Ratchasima (1991-2000) (Margane & Tatong, 2004).

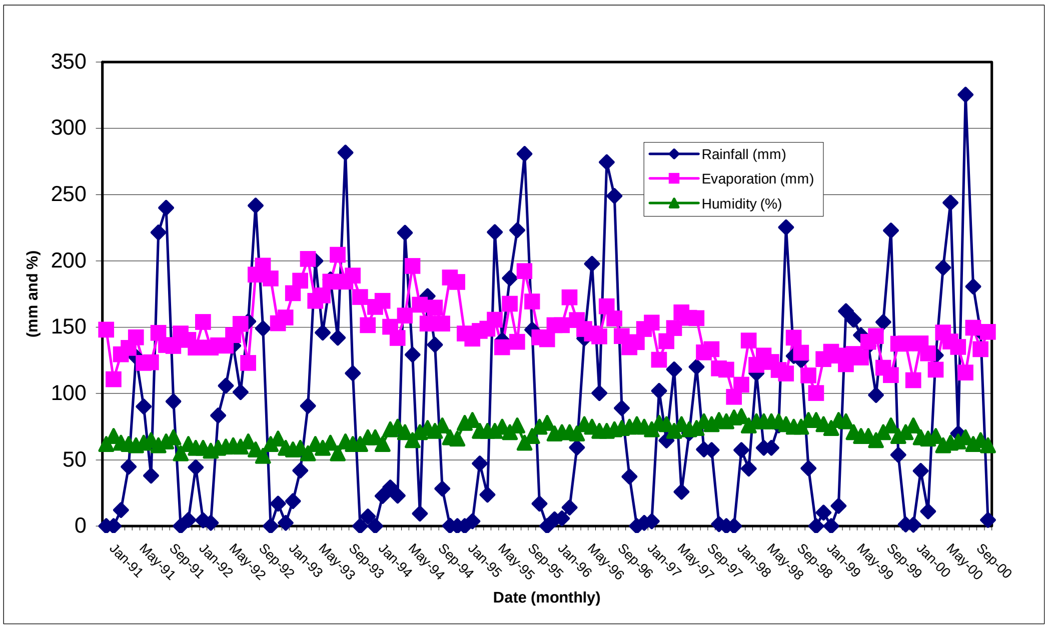

Figure 3.3 Rainfall, evaporation and humidity at Nakhon Ratchasima (1991-2000). (Margane & Tatong, 2004).

In comparison with other areas rainfall is not much lower than elsewhere. However, the evaporation is very high, reaching around 1 750 mm/yr (Nakhon Ratchasima station, 1991-2000). 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. During this time, evaporation is slightly lower than rainfall (Figure 3.4).

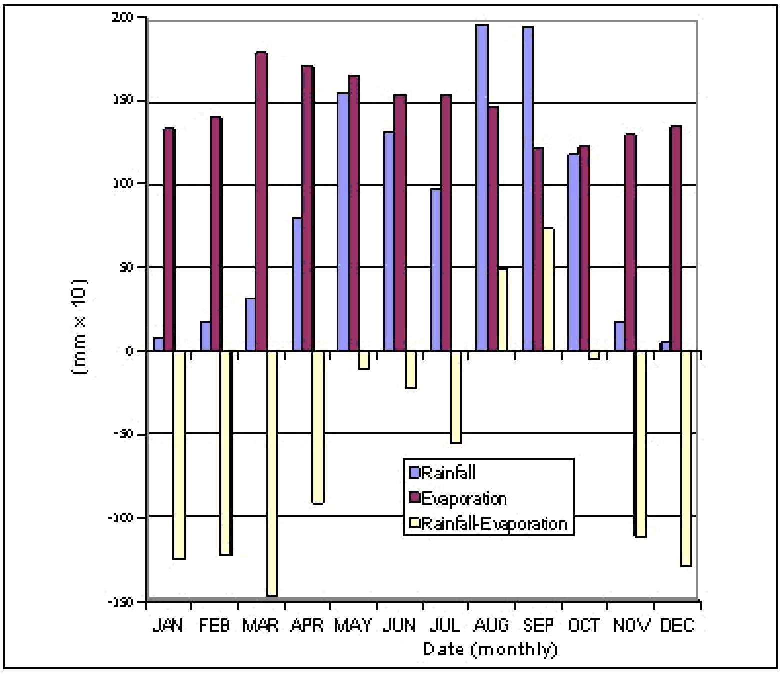

Figure 3.4 Relationship between average rainfall and average evaporation at Nakhon Ratchasima (1991-2000).

3.2.2 Groundwater Conditions of the Study Area

Generally the Khorat Plateau is dominated by Mesozoic sedimentary rocks overlying Palaeozoic sediments, which are exposed on the western and southern margin due to uplift and tilting of 3 to 10 degree to the southeast during the Tertiary. The major geomorphological sequence is the Khorat Group, of which the upper two units of Cretaceous shale, siltstone and sandstone form the upper Khorat aquifer with intake areas along the southwestern escarpment of the Plateau where the study area is located.

Haworth *et al.* (1965) found that artesian conditions occur for water in this aquifer. The Khok Kruat Formation (700 m thick), with thin gypsum veins in joints and cracks, is overlain by the Maha Sarakham Formation (600 to 1 000 m thick), which has thin beds of gypsum and anhydrite separating beds of rock salt 200 m or more thick. Unconsolidated Quaternary sediments up to 50 m thick lie uncomformably over the Maha Sarakham, the landform evolving from erosion and weathering of these sediments and possibly the upper parts of the Maha Sarakham Formation. Haworth *et al.* (1996) also mentioned that aquifers in the near surface alluvium are entirely recharged from rainfall. Salinized soils have been found to coincide with shallow depth or exposure of the Maha Sarakham Formation (Sinanuwong & Takaya, 1974).

Margane & Tatong (2004) studied groundwater in the greater city area of Nakhon Ratchasima, where the study area is located, and reported that there are two types of aquifer in this area, unconsolidated and consolidated aquifers. The unconsolidated aquifers are recognized in alluvial and high terrace deposits and the consolidated aquifers are found in the Maha Sarakham and the Khok Kruat Formations. Depth to groundwater is shallower than 5 m in the northern part and is about 30 m deep in the southern part. Recharge from rainfall in this area is very high. Its values range from 15 to 30 %. From chemical analysis data, groundwater is mainly $CaHCO_3$ type in recharge areas and then the water has an ion exchange with sediments and changes to a $CaNaHCO_3$ or $NaCaHCO_3$ type. If the exchange is completed the water will finally be $NaHCO_3$ type. However, in the salt water area, the western and northern part where the study area is located, NaCl type is predominant.

Available groundwater data in this study includes hydraulic parameters of aquifers and old and new chemical analysis of groundwater, drawdown test, yield, statistic water level, pump test, UTM grid of groundwater wells, which are re-locate by the study of Margane & Tatong (2004). These data can be obtained from many organizations dealing with well drilling but there are a few departments keeping reliable data such as the Groundwater Department (GWD), the Public Works Department (PWD) and the Accelerated Rural Department (ARD). Aquifer systems, depth to the groundwater, recharge and discharge conditions, groundwater types are subjected to study in this part.

3.2.2.1 Aquifer Systems

Margane & Tatong (2004) studied the groundwater system in the vicinity of the greater city area of Khorat (local name of Nakhon Ratchasima Province), which is the major part of the study area of this research. Khorat city is mostly underlain by consolidated rocks which are sandstone, shale and siltstone of Mesozoic age.

Unconsolidated rocks are found only along the Mun and the Lam Takhlong Rivers. Therefore, they divide the groundwater aquifer in the vicinity of Khorat city area into two types of aquifers as unconsolidated and consolidated aquifers.

1) Unconsolidated Aquifers

This sort of aquifer is found in two types of deposits:

1) Alluvial deposits and

2) High terrace and colluvial deposits.

Alluvial Deposits:

Alluvial deposits are found as an aquifer along the Lam Takhlong and the Mun Rivers. The aquifer is formed as a narrow and long strip, which has an axis in east-west direction. Groundwater is stored in sand and gravel layers at depths from 10 to 30 m. The layers were built up by meandering stream channels. Therefore they mainly consist of sand and gravel interbedded with thin layers of clay. However groundwater in these layers is still connected due to lateral change.

High Terrace and Colluvial Deposits:

High terrace and colluvial deposit act as aquifer in the hilly areas south of Khorat City and in the flood plane area, overlain by Alluvial Deposits. Groundwater is trapped in spaces between sand and gravel at two intervals, 20-40 m and 50-70 m below the surface (Groundwater Division, 1988). The two sand and gravel layers are interbedded by fine grained material with thicknesses about 10 m.

2) Consolidated Aquifers

Consolidated aquifers are recognized in the Phu Tok, the Maha Sarakham and the Khok Kruat Formation.

The Phu Tok Formation:

The Phu Tok Formation occupies most of the northern part of the studied area. It is not well cemented and a little soft when compared to other nearby formations. It mainly comprises claystone, siltstone and sandstone. This causes the area where the formation is cropping out to be flat and lowland area. The formation is also easily fractured and is usually a good aquifer. The groundwater can be trapped in both primary and secondary porosity (Srisuk *et. al*., 2003). However, the formation is underlain by rock salt layers which can increase groundwater salinization. The groundwater in this formation is usually salty water contaminated by Sodium Chloride (NaCl). The low salinity groundwater can be found in areas where rock salt layers are very deep buried or fresh water forms a small lens above the salty water in hilly areas. The hydraulic parameters of the formation range from 3.0E-07 to 4.6E-04 m/s or 0.025 to 40 m/d (Srisuk *et al*., 2003).

The Maha Sarakham Formation:

The Maha Sarakham Formation crops out at ground surface mostly in the western and the northern part of the study area e.g. in Dan Khun Thot and Jaturat District. It is found at depths of around 80 to 100 m below ground surface. From the seismic profile, the uppermost surface of the rock salt is generally smooth and gently inclined to the east. Actually, this formation is a very poor aquifer because rock salt does not have primary porosity. Second porosity can be found only in the upper most part due to its plastic property. Hence, groundwater can be trapped only in space between the upper surface of the formation and the overlying rock. Most salt mining get brine water from this space.

The Khok Kruat Formation:
The Khok Kruat Formation is recognized in the southern and western part of the study area as a large hilly area. The groundwater mainly occurs in fractures and bedding planes of sandstone, shale and siltstone. Groundwater quality in this formation is generally good. However, salty water can be found in the areas nearby the contact between this formation and the Maha Sarakham Formation.

3.2.2.2 Depth to Groundwater

Margane & Tatong (2004) measured the groundwater level in 80 wells, especially the DMR wells in the dry season of 2002 and reported that the depth to groundwater in this area ranges from less than 5 to 30 m below ground surface. It depends on topographic levels. The higher topographic levels are, the deeper is the groundwater level. The deepest groundwater is found in the south of Khorat City in the area of high terrace. In this area, groundwater level is about 30 m below ground surface. The groundwater level is shallower close to rivers or low level areas. The shallow groundwater areas are situated in the middle part of the study area and the areas close to Lam Takhong River. Groundwater level in these areas is at 5 or less than 5 m below ground surface.

3.2.2.3 Recharge and Discharge Conditions

Recharge: The main groundwater recharge in this area comes from rainwater. Srisuk (1995) reported that in the Phu Tok Formation the recharge from rainfall ranges from 0.03 to 60%. A high amount of recharge is due to direct recharge through rock fractures. The cover sediments in this area are also mainly sand or sandy soil. This enhances the recharge values. A large amount of rainwater penetrates the soil to become groundwater and flows to the underground. This can be seen from the limited number of streams in this area. Margane & Tatong (2004) estimated the recharge in this rock again from the monitoring wells (Dissataporn, 2002). Results of the recharge estimation range from 15.5 to 29.06 % based on land use as shown in Table 3.7. From this result, it can be seen that in cleared land recharge is two times higher than that in the forest areas.

Table 3.7 The percentage of recharge from different land use types (Dissataporn, 2002).

Land use	Percentage of recharge
Forest	15.50
Shrub	19.62
Eucalyptus	22.98
Barren upland	29.06

Groundwater can also be recharged from water inside reservoirs and irrigation systems within the study area and its surroundings. There are many large reservoirs constructed by blocking main rivers, Lam Takhlong, Lam Chiang Krai. Plenty of small reservoirs were also constructed as ponds by digging or extending swampy areas. Irrigation systems have distributed water in this area since the Lam Takhong was finished in 1969. As the systems are not paved by cement or plastic, water can penetrate and recharge the groundwater.

Discharge: After rainwater recharges the groundwater in high level areas, it flows to low level areas called discharge areas. In these areas, streams, lakes or swampy areas are formed and groundwater discharges from aquifers to become surface water. Mun, Lam Takhlong and Lam Chiang Kai rivers are among those rivers which are supplied by groundwater. Hence, in dry season, there is still some water in these rivers. Other ways of discharge are from plants and human abstractions. The plant abstractions are called evapotranspiration. The amount of water abstracted by plants depends on type of plants and their roots. The longer roots can withdraw groundwater from the deeper part and can lower groundwater level. From this idea, the evapotranspiration in rice fields and in cassava areas is lower than forest areas.

Human abstraction is very low because of the groundwater quality. The groundwater in this area is not favorable for drinking and for washing. The people usually drink rainwater trapped in large jars and use surface water for washing. In many villages, the sources for water traps are changed from groundwater to be surface water, rivers or ponds. Especially in the central part of the study area, people only use water from rainwater and surface water.

3.2.2.4 Groundwater Types

In 2002, 114 groundwater samples were collected from the DMR wells, mainly located in the southern part of the study area and were sent for analysis to the Chemical Analysis Division of the DMR, Bangkok. The major ions were separated into two groups, cations and anions. The cations are composed of Na^+, K^+, Mg^{2+} and Ca^{2+}, while the anions are composed of Cl^-, $HCO3^-$ and $SO4^{2-}$. Then the sum of cations and the sum of anions were calculated. After that the concentration percentage of each ion was calculated by using the sum of its group. Finally, the ion that has the highest percentage was chosen to be the type name of water. However, in some cases the second ion was added to the name because its concentration is equal or higher than 30% of the total ions (Magane & Tatong, 2004).

The main type of cations from the water samples is calcium and sodium. Magnesium type is found in a few samples. The amounts of samples for each type are 59, 49 and 5 respectively. For anions, the main type is carbonate. The other samples are chloride and sulfate types. The numbers of water samples for each type are 75, 26 and 12. When the types of cation and anion are joined together, it creates about 15 full type names. However, there are only 6 large groups of the full types, as shown their distribution in Figure 3.5, as follows;

1) Calcium Bicarbonate ($CaHCO_3$) groundwater is found in the largest number and is predominant in topographical highlands in the southern and eastern part.

2) Calcium + Sodium + Magnesium Bicarbonate (Ca+Na+MgHCO$_3$) Type is the second largest group and occurs in same area of calcium bicarbonate type

3) Sodium Bicarbonate (NaHCO$_3$) Type is the final product of the ion exchange process. Therefore the occurrence area is the same as the two types mentioned above.

4) Calcium+Magnesium+Sodium Sulfate (Ca+Mg+NaSO$_4$) Type is seen locally in the southern part.

5) Sodium Chloride (NaCl) Type is recognized predominately in the northern part influenced by rock salt or it can say that this type of groundwater mainly occurs in Maha Sarakham Formation.

6) Calcium Chloride (CaCl$_2$) Type occurs only in the narrow area along river in the eastern part.

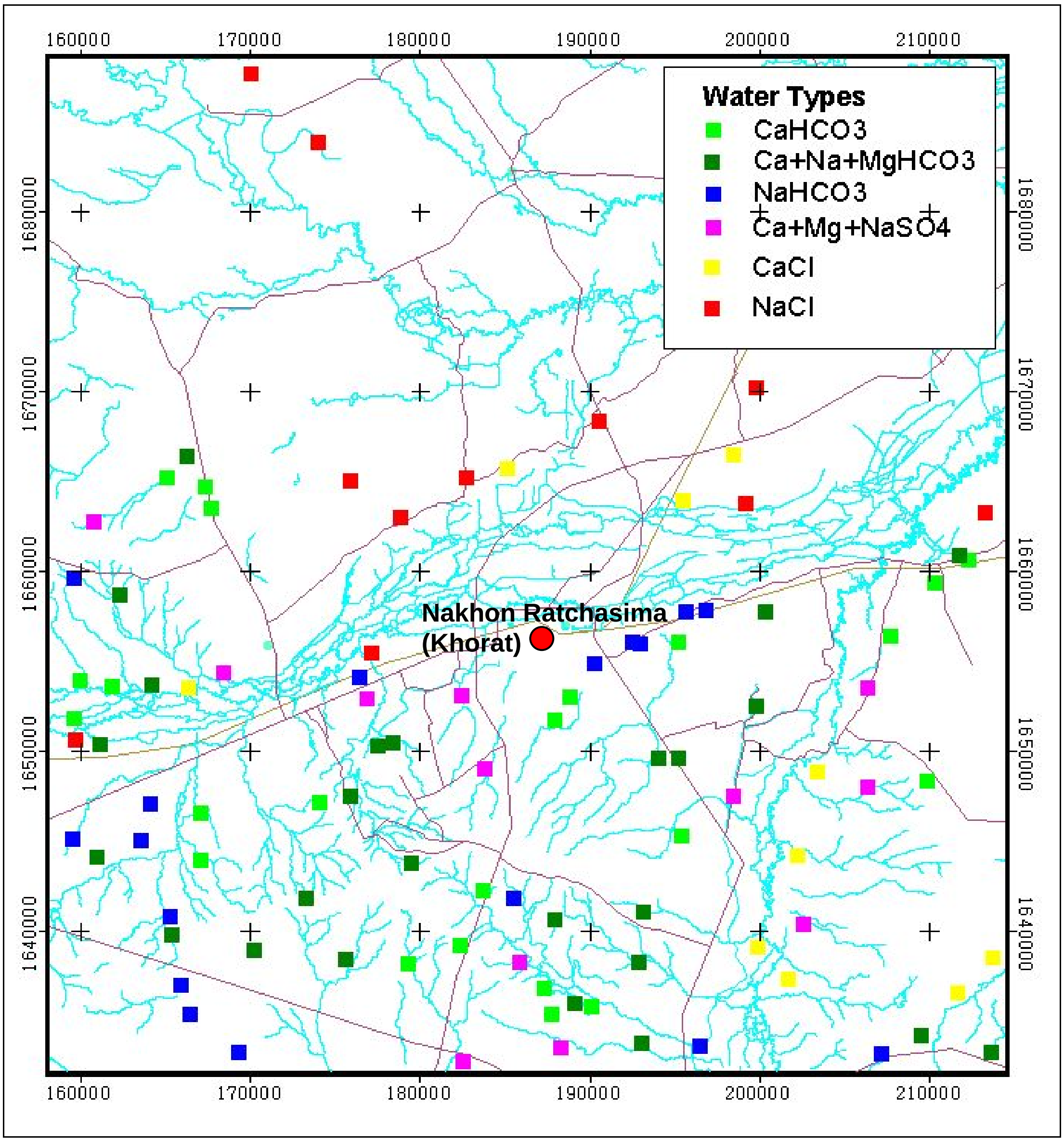

Figure 3.5 The groundwater types from chemical analysis (Margane & Tatong, 2004)

3.3 Causes of Soil and Groundwater Salinization in the Khorat Plateau

Major sources of salinity in the Khorat Plateau are the Rock Salt Members, which consist of three up to 700 m thick rock salt beds, and salts accumulated in form of gypsum, sulfate, and carbonate in the salt-bearing layer of the Upper Clastic Member of Maha Sarakham Formation, and also from some of the salty Plio-Pleistocene sediments.

Sattayarak & Polachan (1990) explained the occurrence of rock salt deposit at the near surface in the Khorat Plateau and pointed out that the rock salt was up-lifted only after the up-lifting of the Phu Phan anticline. Folding and fracturing of the overlying Phu Tok or Upper Clastics rocks have led to rock salt outcrops at the margins of anticlines. At the same time, fractures and faults opened ways for the formation of diapirs. The depth and thickness of the origin rock salt layer are varying. Diapirs and up-lifted salt may be divided by the Phu Tok Formation into single, vertically separated blocks. The near surface occurrence of salt provides ideal conditions for the formation of sinkholes and swamps. This idea applies to sites at the top of diapirs and to areas at the outcrops of the Maha Sarakham Formation as well.

According to the National Land and Water Resources Audit, Australia (2001), two general forms of salinity are recognized as primary and secondary salinity. Primary salinity originated mainly from deposition of oceanic salt by rain and wind. Salt stored in soil or groundwater is concentrated through evaporation and transpiration by plants, and slowly leached downward and stored below the root zone, or transported out of the system. Secondary salinity is the salinization of land and water resources due to land use impacts by people. It includes salinity that results from water table rises from irrigation systems (irrigation salinity) and from dry land management systems (dry land salinity). Both forms of secondary salinity are due to accelerated rising water tables mobilising salt in the soil. For the Khorat Plateau, the primary sources of salinity are salt originated in the ancient drainage basins or inland seas that evaporated during arid periods, leaving behind evaporite deposits. Secondary salinity is the major soil degradation problems in the Khorat Plateau. The problem is caused by groundwater dissolution of salts and accumulating them at the surface.

For the purpose of salinity classification, the present study categorizes the causes of salinity into two types: natural causes and human activities causes, according to the origins of the salinity.

3.3.1 Salinity Caused by Natural Causes

Salinity may be caused by natural processes such as rainfall, humidity, evaporation rate, topography, discharge and recharge area conditions and groundwater flow systems of the region, etc.

Naturally, the development of saline soil and saline groundwater is related to the flow of groundwater. Under saturated flow conditions, when the moisture content is at or above field capacity, groundwater is able to move under the influence of gravity. In saturated flow systems, excess of groundwater builds up in a recharge area to the point where lateral groundwater flow occurs. As the groundwater flows between particles of rock and soil, it dissolves and transports soluble salts. The groundwater emerges at the soil surface in a discharge area. When the water evaporates, the salts are left behind on the soil surface. Over time, the salts accumulate in the discharge area, and eventually the salt concentration becomes so high that plant growth is restricted.

Groundwater can also move under unsaturated conditions through the smaller soil pores by the process of adhesion. That is, when soil moisture content is close to field capacity, soil particles will yield water molecules to other soil particles with lower moisture levels. Unsaturated flow is common around sloughs, dugouts and other water bodies. Like saturated flow, it can dissolve and transport salts to the soil surface.

Saturated groundwater flow systems may be local, intermediate or regional (Kwiatkowski *et al.*, 1994). In a local flow system, the recharge area is usually within a few hundred meters of the discharge area. An intermediate system consists of several interconnected local systems, and extends beyond 1 km (0.6 miles). A regional system has its recharge area at the water divide of a basin while the discharge area lies at the bottom of the basin. Regional systems may extend over several kilometers.

Groundwater flow causing the salinity in this study can be classified as two types:

1) Shallow groundwater interflow and

2) Deep groundwater flows (or artesian flow) with the help of capillary rise effect, based on the depth of the groundwater flow.

1) Shallow Groundwater or Shallow Interflows

The shallow groundwater flow or shallow interflow flow, including runoff causing salinity concept conceives that the salt, originated directly from weathering of the Maha Sarakham Formation and/or some salt accumulated in the Upper Clastic Members, was dissolved and transported from nearby uplands through shallow interflow, surface flow or runoff to the low-lying areas. The salinization by the shallow groundwater flow and/or surface flow is responsible for a great number of saline areas (Löffler & Kubiniok, 1988).

This concept was previously proposed by several papers published in the seventies and eighties, e.g. Sinanuwong & Takaya (1974a and 1974b) or Wongsomsak (1986). They consider areas of exposed or outcropping “Rock salt members” as the sources of the soil salinity. According to this theory, rain water dissolves the salt from the “salt-releasing units” (elevated ground at the interior margins of the basins) and with the short transportation mechanism of the surface and subsurface water, the brines migrate to the “salt-receiving units” (low-lands and valleys), and lead to salt crusts as results of evaporation. A modified version of that view conceives the origin of the salt crusts in the frequent flooding parts of the Khorat Plateau. The salt was dissolved from near surface rock salt layers or some salt accumulated in the Upper Clastic sediments after heavy rainfalls in the rainy season and surface water transports saline water to those areas and salt encrust as a result of evaporation. The generalized model of the shallow groundwater flow is shown in Figure 3.6.

Shallow interflow operates mostly on a local scale. It is particularly obvious around the foot slopes of low hills and mounds that consist of the spoils of former salt production activities, and natural hills and ridges with bed rock containing salt close to the surface.

An example of shallow interflow associated with rising groundwater causing salinity occurs at 30 km south-west of Khon Kaen Province at Ban Phra Yuen Village and this site is under investigation by the Soil Salinity Division of the Department of Land Development. The area consists of low broad ridges with wide valleys, which are under rice or used to be under rice cultivation. From the topographic situation it is evident that the salt in case must have reached the lower slopes by shallow interflow, whereby a rise in groundwater must have brought salt close to the surface and caused the shallow salt water seepage. In addition to the surface salinization, severe soil erosion has set in and removed much of upper soil horizon exposing the even more heavily salinized subsoil.

Takaya *et al.* (1984) reported another good example for salinization by shallow interflow. In their study, a small hill of partly weathered rock of the Maha Sarakham Formation rises some 10 m above the surrounding plain. The bed rock is overlain, as is common throughout the Khorat Plateau, by 1 – 1.5 m of fine sand. A piezometer installed at the foot of the hill showed a piezometer level slightly above the plain surface and the water was reported as saline water with an EC of 1100 $\mu S.cm^{-1}$. Three pits dug into different levels along the slope indicate that the water is becoming increasingly saline as it moves downslope by shallow interflow, and it is believed that the water picks up salt as it moves through the weathered Maha Sarakham Formation.

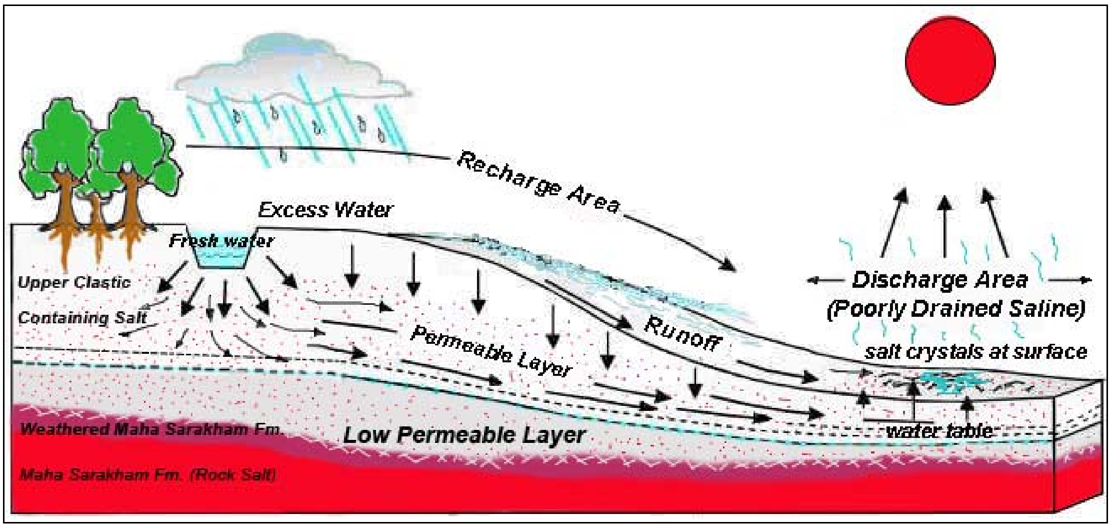

Figure 3.6 The conceptual model of the shallow interflow or shallow groundwater flow system.

Williamson *et al.* (1989) made an intensive study of the groundwater hydrology and salinity of a 5 000 ha area near Nakhon Ratchasima Province, from June 1985 to September 1988. Their objective was to determine the source and flow path for water and salt of the upper 20 m of the regolith and to provide a basis for establishing appropriate management strategies. The land use in the study area was divided about equally into agricultural woodland in the uplands cropped to cassava and kenaf and salt-affected rice paddy fields in the valleys with a traditional salt making operating at one valley location. They showed that groundwater flow from the uplands converges in the central valley, where the major salinization occurs. In a larger context, groundwater flows from this area to the north-east where terraces and flood plains form part of the upper reaches of the Mun River. They also reported that three recharge areas contributing to the movement of salt into the salinized valley were identified and the salt outflow estimated to be about 32.3 tons.d^{-1}. Their conclusions can be summarized as follows: deforestation has substantially decreased transpiration and interception and provided a source of water for the salinity problems; halite in the Maha Sarakham Formation or secondary deposits of salt in more recent overlying unconsolidated formations were identified as the source of salinity; the mechanism for salt redistribution is the water flow down a vertical displacement of 15-30 m, from recharge area to valley; the saline areas have been found where the flow path is upward towards the soil surface or where the spatial variations in hydraulic conductivity produce a convergence of flow.

Salinization by shallow groundwater is mostly responsible for a great numbers of saline areas, and it is most commonly associated with seepage of water from man-made ponds that are ubiquitous throughout the Khorat Plateau.

However, shallow interflow and/or surface flow can cause salinity mainly during the wet season when the shallow groundwater is constantly recharged with fresh water. It also can not explain the great expanse of salinized land in the large alluvial plains such as the Tung Kula Ronghai because there is not just sufficient bed rocks area in the near vicinity and the salinity effects are spread rather irregularly throughout the plain. The saline areas in the Tung Kula Ronghai area occur as randomly distributed spots, 5 – 25 m in diameter, and can be well observed in air photos (Löffler & Kubiniok, 1988).

2) Deep Groundwater Flow and Capillary Rise Effect

The salinity caused by deep groundwater flow is normally related to the capillary rise effect and artesian pressure flow system. The capillary fringe concept proposes that the main cause of salt reaching the surface is a general rise of water tables to the capillary fringe and consequently the rise of salt to the surface. Salt is supposed to be brought into the aquifer by long distance groundwater flow from distant salt-bearing rock strata. For saline soils to form, the water table needs to come close enough to the soil surface to allow capillary (wick) action to raise the groundwater to the soil surface. In general, the water must be within 2 m (6 ft) of the soil surface for this occur, but the critical depth (the depth beyond which water cannot wick to the soil surface) varies with soil texture (Henry *et al*. 1987). The water table rise caused by the capillary force is responsible for salinization in the large alluvial plains such as Tung Kula Rong Hai region (TKR), a vast alluvial plain covering about 337 000 ha in the southern part of the Khorat Plateau (Löffler & Kubiniok, 1988).

Tung Kula Rong Hai is one of the good examples of salinity caused by deep groundwater flow and capillary rise effect. The TKR covers parts of five provinces (Roiet, Surin, Sisaket, Maha Sarakham and Yasothon) and is bordered in the south by the Mun River. Most of the area is flat with a gentle slope downward from west to east. Salinity in TKR has been studied using a multidisciplinary approach. The relationship of excess salinity to stratigraphy, hydrogeology, land use and soil has been assessed at specific study sites and at a more general level for all of TKR. TKR is extensively deforested with less than 2 percent under forest. It is estimated that only 6 percent of TKR is totally free of salinity (Australian Development Assistance Bureau, 1978). The most severely salt-affected lands are located within the alluvial plain, where rice cultivation is dominant.

The main cause of salinity is watertable rise (between 3 and 8 m in various sites) and the presence of shallow saline watertables from which salts rise to the root zone. The shallow saline watertable has developed because of increased recharge to the aquifer resulting from forest clearing, mainly in upland areas both within and to the north-west of TKR. Within TKR about 20 percent of the areas provide recharge to shal1ow, local, low salinity flow systems (Australian Development Assistance Bureau, 1978). Recharge on uplands supply deeper, long distance, more saline flow systems. Shallow flow systems are divided into unconfined and semiconfined flows. Deeper, longer flow systems flow through shales and sandstones to emerge in the deeper parts of the Quaternary sequence away from the uplands in TKR. These long, deep flow systems dissolve salt from a variety of sources of solid salts in the Cretaceous and Tertiary Maha Sarakham Formation. Upward movement of these saline waters contributes to the salinization of the area.

Löffler & Kubiniok (1988) published an idealized block diagram of Tung Kula Ronghai Plain showing the stratigraphy and a model of soil salinization under natural vegetation and under deforestation conditions (Figure 3.7). They suggested that under vegetation conditions, water use and evapotranspiration are high, while under deforestation the groundwater use and transpiration are reduced. Due to the presence of a confining clay layer in the plain, the groundwater in this area is under artesian pressure. A perched water table develops during the rainy season and is usually not connected with the main aquifer.

Depth to the upper most rock salt layers in this area ranges from 70 to 100 meter. However, the formation is not impermeable because there are factures. Therefore rainwater can penetrate through the formation to dissolve the rock salt. Then the salty water is moved by a long groundwater flow from a recharge area to a discharge area, where is usually a low level area. In the discharge area groundwater level is close to the ground surface. Then the capillary force will withdraw groundwater to ground surface. Withdrawal distant of the capillary force depends on space between sediment grains. The smaller space is in sediments, the higher distance of capillary force is found. The relationships between sediments and capillary rise from Fetter (1994) are as shown in Table 3.8.

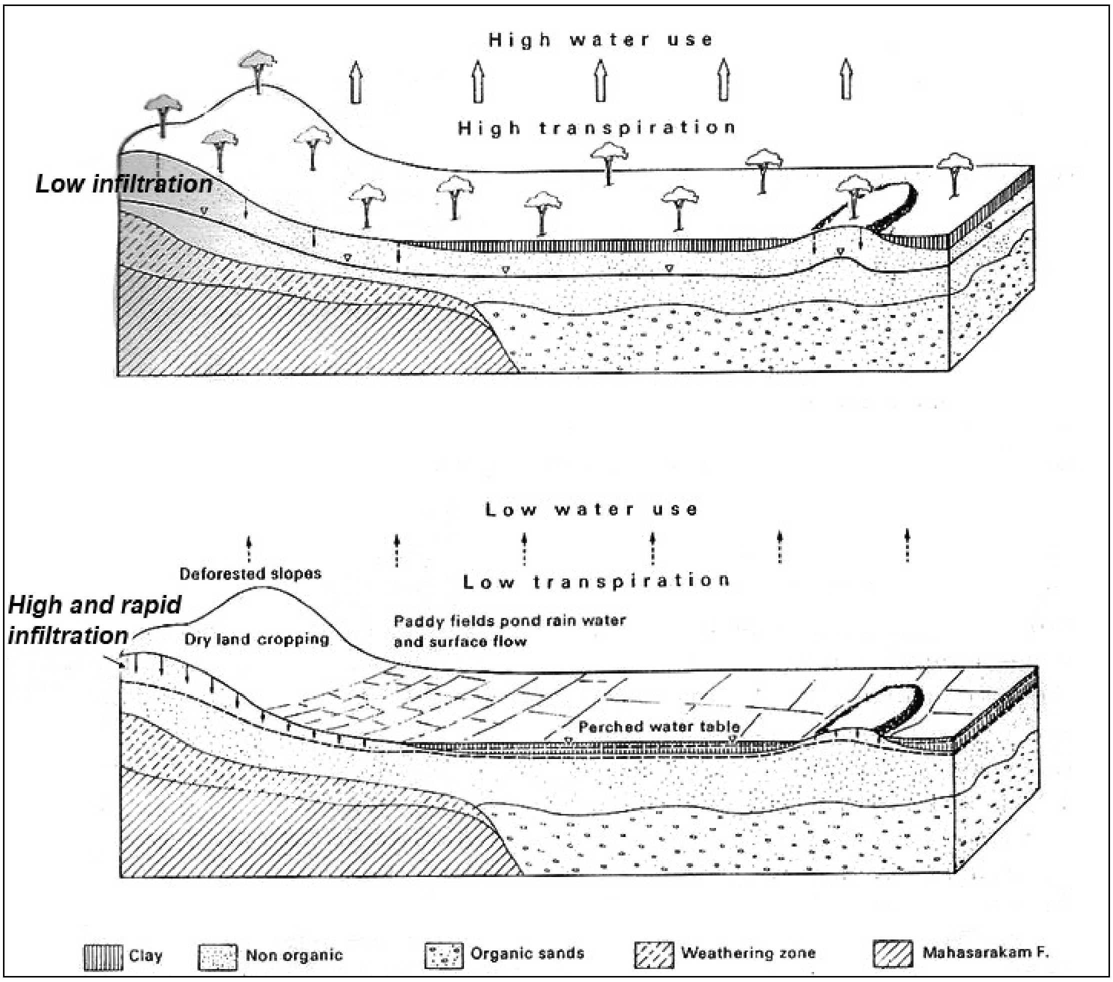

Figure 3.7 Idealized block diagram of Tung Kula Ronghai showing the stratigraphy and a model of soil salinization under natural vegetation (above) and under deforestation (below) condition (Löffler & Kubiniok,1988)

Table 3.8 The height of capillary rise in sediments (Fetter, 1994).

Sediments	Capillary rise (m)
Fine silt	7.50
Coarse silt	3.00
Very fine sand	1.00
Fine sand	0.50
Medium sand	0.25
Coarse sand	0.15
Very coarse sand	0.04
Fine gravel	0.02

From Table 3.8 the capillary can draw groundwater up to 7.5 m in fine silt. This means, groundwater that is shallower than 7.5 m can be drawn up to the ground surface. As water evaporates from the ground surface, the capillary force can replace it by drawing upward the groundwater. In case of saline groundwater, dissolved salt cannot be evaporated as water. It will be accumulated at the soil surface. If this process can continue for long period, the accumulated salt will be higher until it can be seen as white path on the soil surface.

After the salt path is accumulated on the soil surface, it will be removed by rainfall in rainy season. The salt path will be formed again in the next dry season if the groundwater level is still close to the ground surface. Therefore in the first flood or in the early of rainy season, flooding water should not be kept in rice fields. It flows to rivers or stream. The flooding water washes salt path out and decrease the concentration of salt in the soil.

The capillary fringe due to the water table rising up concept coincides with the “Fault Concept” which is the tentative concept favoring the rise of the salt along fractures or faults. This “fault concept” was presented by geologists from the Suranaree University of Technology (SUT), Thailand, and by hydrologists from Khon Kaen University, Thailand, (Srisuk *et al*. 1994, 1995 and 1996). The fault concept considers the deep groundwater flow, artesian flow, and convection through the “Upper Clastics” as the reason for the dissolution of salt from the Maha Sarakham Formation. The dissolved salt rises to the surface using increased permeability along fault and fracture planes.

Srisuk *et al*. (1994) studied the groundwater flow and salinity at Ban Nong Khai Nun Village, Khon Kaen Province. They found that the saline water at Ban Nong Khai Nun site is related to groundwater flow in sand, silt and clay of Quaternary deposits of the Chi River, and in sandstones, siltstones and shales of the Phu Tok and the Maha Sarakham Formations. The distribution of observed flow-related manifestations of hydraulic heads, and of hydraulic conductivity values indicates that local groundwater flow (100 to 400 m flow distance, and at 20 to 90 m deep) and regional groundwater flow (5 to 10 km flow distance, and at 100 to 200 m deep) systems are the main agents that carry the high salinity water to the land surface. Geologic structures (faults or fractures), such as Huai Chan Creek and Chi River which are the river courses developed along the natural fault and act as vertical impermeable boundary of the groundwater flow. Topography also plays a significant role in controlling the pattern and intensity of natural groundwater flow. Saline groundwater moves upward from the water table to where the water table level is less than 1.5 m; it will move to the surface through the capillary fringe by the evapotranspiration processes. The diagrammatic representation of conceptual groundwater flow at Ban Nong Khai Nun, Khon Kaen Province, NE Thailand, is shown in Figure 3.8. A hydrogeologic profile in south – north direction of this area shows that the deep groundwater convection (regional flow) flows downward and dissolves the rock salt bed of Maha Sarakham Formation, about 100 m deep from surface, and bring up brine to the surface as shown in Figure 3.9.

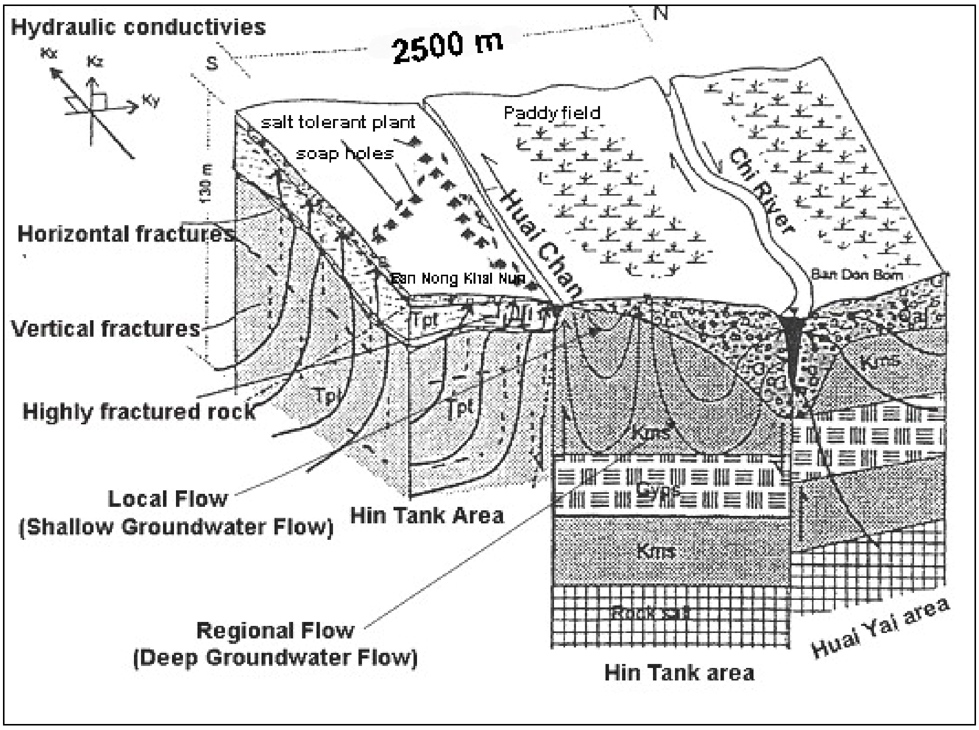

Figure 3.8 Diagrammatic representation of conceptual groundwater flow at Ban Nong Khai Nun, Khon Kaen Province, NE Thailand (after Srisuk *et al*., 1994).

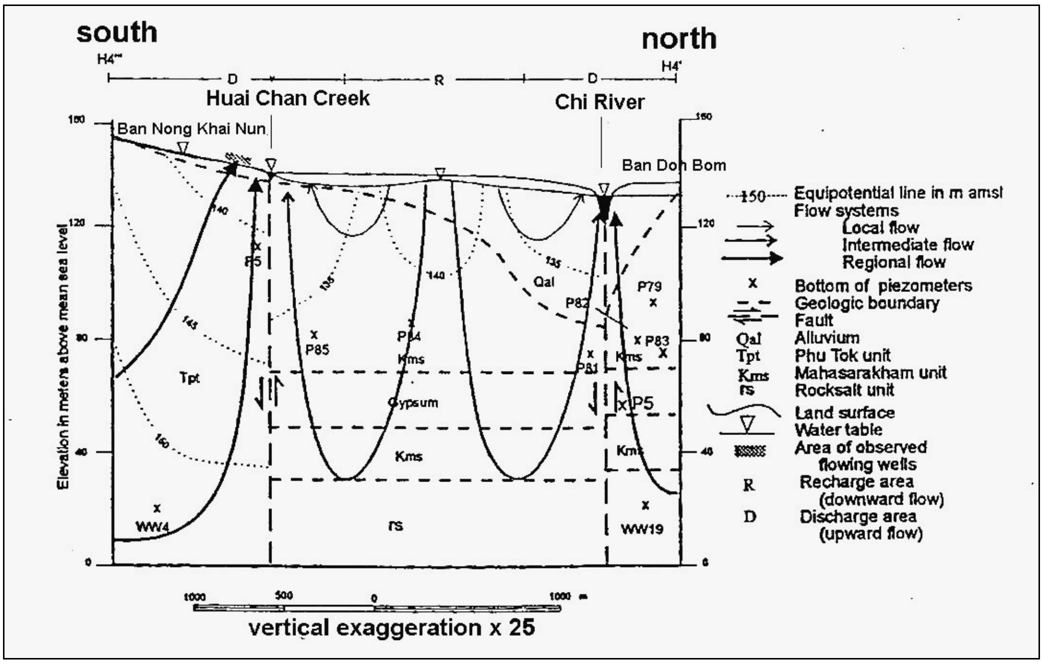

Figure 3.9 Hydrogeologic profile in south – north direction of Ban Nong Khai Nun, Khon Kaen Province showing the deep groundwater convection (regional flow) down to the rock salt unit of Maha Sarakham Formation (after Srisuk *et al.*, 1994).

3.3.2 Salinity Caused by Human Activities

Various human activities are responsible for the spread of salinization in northeastern Thailand. These activities include deforestation, the construction of reservoirs, salt making and irrigation (Arunin, 1987). However, it is important to note that the largest part of the area affected by salinity has been caused by forest clearing. The following sections describe the effects of the above mentioned causes.

1) Deforestation

The total forest area in Thailand in 1961 was approximately 28.67 million ha or 56 percent of the Country. By 1988 this area had decreased to 14.38 million ha or 28 percent. In northeast Thailand, forest cover had declined from 42 percent (7.4 million ha) to 13 percent (2.36 million ha) during the period 1961-85. Deforested areas have been used for upland cash cropping. According to Rigg (1987), since the end of the Second World War, upland cash cropping has spread in Thailand. These crops are grown on higher ground unsuited for cultivation of rice. In north-east Thailand there has been an accelerating expansion in the land planted to kenaf, cassava *(Manihot utilissima)* and other crops. Kenaf was far more suited than maize to environmental conditions over much of the north-east and with the rise in the kenaf price between 1959 and 1961 much upland crop farming shifted from maize to kenaf. Like kenaf, cassava is agronomically suited to the northeast, but, in addition, it is an extremely flexible crop that can be cultivated with a minimum of labor and cash input. Cassava can be grown on the poorest of soils without the need for fertilizer. Moreover cassava plantation is more profitable than kenaf. Therefore large areas recently cleared and never previously planted by kenaf were used for cassava cultivation.

The salinization of rice paddies and water reservoirs is a very recent development and is associated with deforestation in the upland soils for producing cash crops as above mentioned. Subsequent changes in the hydrologic conditions following land clearing and replacement of deep rooted trees with shallow rooted crops (cassava, kenaf, etc.) increased the natural recharge of aquifers and resulted in saline seepage on lower slopes and valley floors. The deeper saline groundwater is wel1 below the range of capillary movement, but as it is commonly artesian, it is possible that saline groundwater moves upwards under pressure. In some areas, shallow saline groundwater may be formed by the groundwater flowing through a shallow salt dome and moving up from depths below 10-15 m (Arunin, 1984).

2) Salt Production

Salt production is another cause of human-induced salinization. Krairapanond *et al.* (1992) described salt production in north-eastern Thailand and its impact on land and water resources. The following summary is based on their account.

Salt production in north-east Thailand began in a primitive manner for household consumption. Soils with patchy crusts of salt on the surface were dissolved and then boiled to crystallize salt. Salt produced by this method was practical to every local livelihood in this region. Traditional salt production had been changed to be the commercial process when saline groundwater was found that it has very high salinity as 50 000 to 60 000 mg/l at Borabu District, Maha Sarakham Province, in 1969.

Three different types of rock salt mining have been practiced in northeast Thailand. Two traditional operations are boiling and sunning methods for local investors and one newly introduced advanced technology is called solution mining. These salt making processes are as follows:

- The boiling method is a primitive approach to producing salt. In this case the soil is used, the white crust of salt is collected from the soil surface, dissolved in water and filtered. Then the dissolved salt is crystallized by boiling. When high saline groundwater is used, the operators just boil it to produce salt.

- The sunning or on-farm method has two types of operations. In the first type, natural brine or saline water is pumped out from 30-190 m below the surface and is processed into salt on a farm by sunlight-induced evaporation. In the second type, freshwater is pumped down to dissolve the underground rock salt and then the water containing dissolved salts is crystallized by sunlight.

- Solution mining consists of pumping water down to about 200 m below the land surface to dissolve the rock salt, which is then pumped up in the form of salt water to the surface. The salt water is later treated at a high temperature to produce salt. This method seems to effectively protect the environment from the adverse effects of the operation.

In general, scattered rock salt mining can be found mainly in the areas of Sakon Nakhon, Nakhon Ratchasima, Udon Thani, Maha Sarakham, Nong Khai and Roiet Provinces. In these areas shallow deposits of rock salt are observed at depths of less than 100 m (Figure 3.10).

When salt production escalated after 1971, many forest areas were largely deforested because of the boiling method used to crystallize salt water. This boiling method was soon limited by a shortage of fuel wood.

The practice of salt production pollutes downstream rivers and paddy fields, destroying rice crops and killing fishes. For example, the Nong Bo Reservoir in Maha Sarakham Province, which is a middle-sized reservoir, was damaged by the high salinity of waste waters from salt farming. The salinity of water in the reservoir reached nearly 100 000 $mg.l^{-1}$ in 1990, affecting farming families along the Siew River (a tributary of the Mun River) by the release of water from the reservoir for agricultural purposes (Krairapanond *et al.*, 1992).

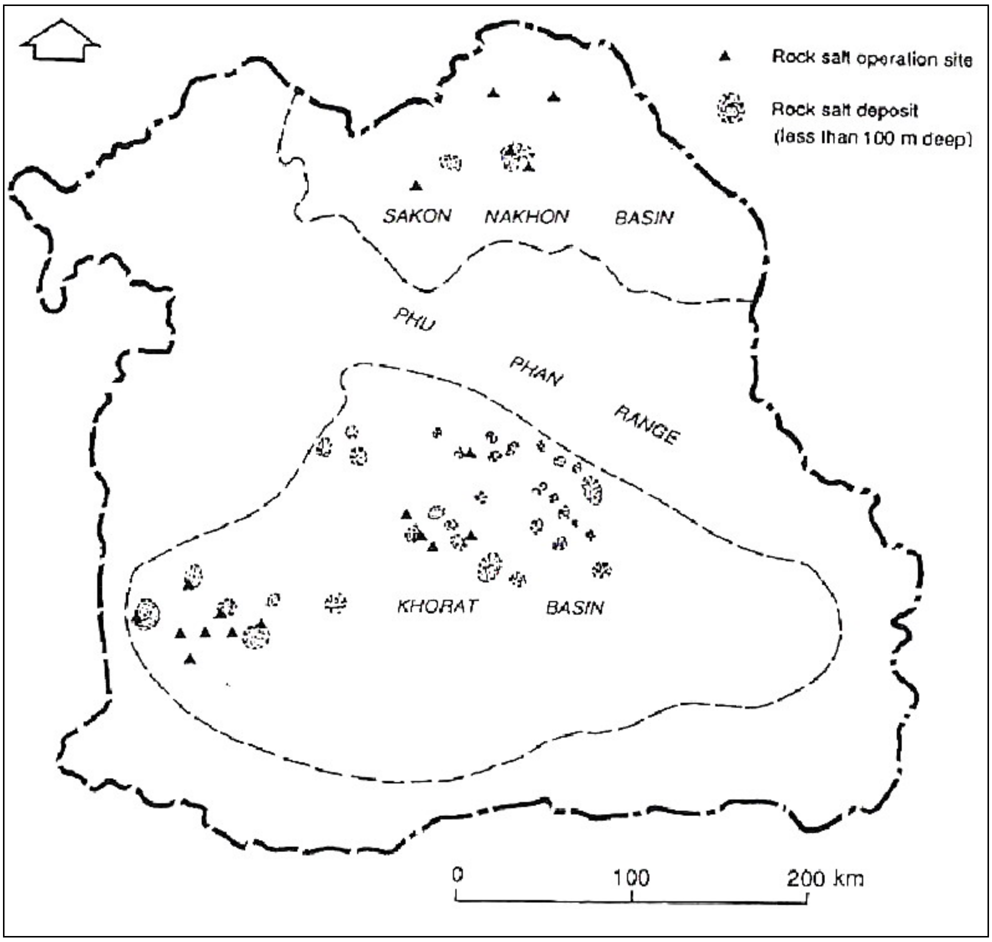

Figure 3.10 Rock salt deposits and rock salt mining operations in the northeast of Thailand (Krairapanond *et al.*, 1992).

Although salt making has been blamed for the expansion of salinity of the Siew River, Williamson (1985) expected that the groundwater inflow along the river with salt sources at depth in the Maha Sarakham Formation could be as large if not much larger than the salt making input. However, the effect of different processes contributing to the salinity of the river needs to be quantified.

3) Construction of Reservoirs

Construction of reservoirs in areas with shallow saline groundwater also causes salinization and widespread environmental problems. Salinization occurs in the vicinity of these reservoirs and has spread out over an even wider area from the reservoirs.

Arunin *et al.* (1988) investigated the impact of 132 reservoirs on salinization in the northeastern Thailand during the three-year period 1984-86. Reservoirs have been located on soils with six salinity levels as defined by the soil salinity map produced by the Land Development Department. In their study, reservoirs have been classified into five groups according to their capacity, ranging from 50 000 to more than 1 000 000 m^3. Their report indicates that: the capacity of the reservoirs had no effect on water and soil salinity; electrical conductivity of reservoir water has been increasing every year due to the inflow of saline water into reservoirs; and salinities increased during dry periods and decreased during wet periods. Their report shows that seven reservoirs (5.3 percent) have an EC value of greater than 3 000 µS cm-^{1} and 27 reservoirs (20.5 percent) have a lower EC of 700 to 3 000 µS cm^{-1}, while in 98 reservoirs (74.2 percent) the EC has been lower than 700 µS cm^{-1}. They also found that a high percentage of reservoirs constructed on saline areas are salt-affected. For example, all reservoirs built on the severely saline areas have moderate to high salinity levels. Their investigations also show that water in the reservoirs tends to become saline a few years after construction. Reservoir salinity reaches high values of 24 000 and 16 000 µS cm^{-1}, respectively. It should be noted that in the case of the Nong Bo Reservoir, discharge of the effluents from the salt making operations had a major effect on the salinity of the reservoir's water.

The water salinity in reservoirs comes from its stored water containing salt or saline derived from upstream sources. Another possible cause is the leakage water from reservoir flowing downward and re-disturbs the saline groundwater underneath the reservoir that rises and mixes with fresh water in the reservoir. The risen saline groundwater can also cause soil salinity when it reaches the capillary fringe and evapotranspiration can play its role.

4) Irrigation

Salinization of land and water resources of north-east Thailand caused by irrigation is not well documented. However, secondary salinization in irrigated areas has been reported from the Nong Wai irrigation area in the Khon Kaen Province, Kumpawapi south of Udorn, the Lam Pao irrigation scheme at Kalasin Province and Un in Sakon Nakhon Province (Arunin, 1984) but no detailed information is available. According to Arunin (1992a), in Lam Pao and Nong Wai, with respective irrigated areas of 41 000 ha and 11 000 ha, about 10 percent of each area are affected by secondary salinization. The cause of irrigation salinity is similar to those of reservoir salinity. Details of irrigation salinity process and other salinities are discussed later in Chapter 6.

3.4 Salinity Classification

The purpose of classifying salinity is to identify various types and recommended their management practices. Salinity maps also provide an inventory of the salinity problem and an excellent tool for local agents. Analysis of the data allow policy makers to design and target programs specifically to the extent and the nature of the problem.

Based on hydrogeology, surface water flow, geology, topography, and soils, this study classified salinity in the study area into three main types:

1) Salinity along weak zone,
2) Salinity in depression areas, and
3) Salinity affected by reservoir and irrigation system.

3.4.1 Salinity along Weak Zones

Salinity along weak zones occurs where a permeable, water-bearing layer, such as a sandy layer, coal seam or fractured bedrock layer, outcrops at or near the surface. The salinity process takes place in the weak zone such as the bedding plains between two rock types, river courses, fractures, faults, and fissures. Saline seeps occur in rows along a slope at similar elevations. In most cases, this form of salinity is a form of primary salinity (i.e. it has developed naturally over geologic time). Salinity along a weak zone may be categorized into subclasses as salinity along a rock boundary, salinity along a lineaments and salinity along a river course.

3.4.2 Salinity in Depression Areas

This type of salinity occurs in depressions or drainage courses. The area is salinized by a shallow interflow system in that surface water flows slowly over and is trapped temporarily in the low lying areas until the water drains off and/or infiltrates the soil. Once the surface water has disappeared, groundwater from the water table rises by capillary action to the surface into the previously pond area. When the water table reaches the capillary fringe, capillary action and evapotranspiration play important roles to bring up brine and crystallizes salt at the surface.

A similar form of depression salinity is slough ring salinity. This type of salinity occurs as a ring of salt immediately adjacent to a permanent water body. Water infiltrates from the pond into the permeable upper soil layer and moves laterally upslope, as shallow groundwater in an unsaturated state circulates through this layer. The water may also flow downward, raising the water table. Water from the lateral unsaturated flow and capillary rise from the water table emerges at the surface where it evaporates, leaving salts at the edge of the slough.

3.4.3 Salinity affected by Reservoir and Irrigation Systems

This type is dominant where leakage from reservoirs contributes to seeps. In case of reservoirs causing salinity, because reservoirs or dams are mostly constructed and located in large low lying horizontal plane where water table is not too deep, leakage water from reservoir would add to the groundwater, therefore, saline groundwater underneath reservoir site is disturbed and emerged to surface causing salinity to surrounding areas. These salinity types mainly occur in reservoirs and dam sites throughout the study area and the Khorat Plateau.

In case of canal seepage salinity, leakage water from canals contributes to seeps as occurred in reservoir case. This is because canals are normally dug and located along a topographic break. Fresh water, or sometimes salinized water, from canals infiltrates the surrounding area and causes salinity as in the reservoir salinity case.

The salinity mechanism, the distribution and the related geologic feature both subsurface condition and its reflected feature on the satellite image of each salinity type will be discussed in detail in Chapter 6.