CHAPTER II

LITERATURE REVIEWS

2.1 Analysis of Subsurface Investigation

2.1.1 The Electric Logging

Electric logging is a method for measuring the electrical properties (Spontaneous Potential and Resistivity) of the strata penetrated drilled wells. These properties are continuously measured through the electrode, which is lowered into the borehole via electric cable. In general, the spontaneous potential (the so called SP) and resistivity are simultaneously recorded on the same log-chart. The SP (in millivolts) is on the left–hand side of the log-chart, while the resistivity (in ohm–meter) is recorded on the right. The electric log is valuable in groundwater investigations for determining type of formation, permeable beds, thickness, water quality, and correlation for subsurface mapping. However, interpretations of the electric log for formation characteristics are considered to be one of the most important and difficult phases of the log. Experience is essential in both qualitative and quantitative interpretation. However, it is recommended here that the interpretation have to correlate with the assistance of cuttings.

2.1.2 The Spontaneous Potential Logging (SP log)

The Spontaneous potential log or the SP log has been known and widely used for location of permeable beds traversed by drill hole. In electric logging practice, the SP log will be correlated and interpreted with the resistivity curves. Usually, the SP log consists of a base line, more or less straight, having excursion on "peak" to the left or negative. The base line frequently has been found to correspond

to an impervious bed, generally shale, while the peaks are usually found opposite permeable strata. Measurements which will indicate positively the presence of permeability in the formation, and which will give accurately the boundaries of the permeable zones, are of great important in groundwater development.

2.1.3 The Risistivity Logging

Electricity can pass through earth formations because of the mineralized (formation) water they contain. Thus, subsurface formations have some measurable resistivities because of their water content. The Resistivity of a formation depends largely on the resistivity of the waters present in that formation, both in amount and arrangement of such water present in the formation. However, these figures may be changed due to some effects of salinity and temperature. Normally, the resistivity of water decreases as the amount of chemical therein increases and/or its temperature increases.

2.1.4 Interpretation of the Environmental Deposition of Sediments

The SP curve analysis is a useful method to delineate the geometry of sand units. Most definitely, the porous and permeable sand is one criterion that can be employed in interpretation the depositional history of that unit.

Most certainly, the thickness of the porous and permeable sands is one criterion that can be used in interpreting the depositional history of that unit. It was shown that the very high negative response with respect to the shale line indicates clean, well-sorted sand, and low negative deflections within the shale line indicate a shaly sand. As a result, if there is a very clean break between the sand and shale, as indicated on the SP curve, this implies that there is a rapid change in the energy distribution. These rapid transitions are likely produced in areas where high differences in water depth or energy distribution cause considerable variation in a

depositional environment. On the other hand, if one observes a broad transition on the SP curve, it would imply that this sequence was under more stable conditions during deposition and small variations in the sedimentary process.

A highly serrated shape on the SP curve is observed quite often in a number of areas, and suggests rapid transition and non-equilibrium conditions. When the SP response decreases upward (moves toward the shale line) it would suggest a decreasing grain size of sedimentation and an overall decrease in energy, as in a fluvial environment. On the other hand, if the SP response increases upward or becomes more negative, one would expect coarsening upward which would be typical of a regressive marine environment where the energy is higher at the top of the sequence.

The four that are most obvious on the SP log are as follows:

1) **Regressive marine.** This results from higher energy near shore sediments effect the increasing energy distributions of the regressive marine process that are progressively deposited over lower energy offshore sediments (Fig. 2.1)

Figure 2.1 The SP curves show regressive marine environment.

2) **Channels and bars.** The opposite curve shape with decreasing energy towards the top of the section can be seen in the examples in Figure 2.2. This type of

energy distribution is commonly developed in fluvial environments where the basal unconformity is overlain by massive, well sorted clean sands which in turn are overlain by inter-bedded silts, sands, and clays, with the amount of clay increasing towards the top of the section.

Figure 2.2 The SP curves show channels and bars environment.

3) Transitional-deltaic. SP curve shapes, which show abrupt transitions both on top and bottom, suggest a mechanism of sedimentation related to both fluvial and regressive marine processes. Massive deltaic sands indicate a distribution of lithologies, which produce this type SP curve (Fig. 2.3).

Fig 2.3 The SP curves show distributary environment.

4) Transgressive. Transgressive units are most typically quite thin and difficult to identify on the SP curve. However, when they are associated with sand sequence there is often a small resistive unit that is developed on top of the sequence. This combination of resistivity kick and decreased SP are the criteria that are used to delineate this transgressive unit. Typical curve shapes for this environment can be seen in Figure 2.4.
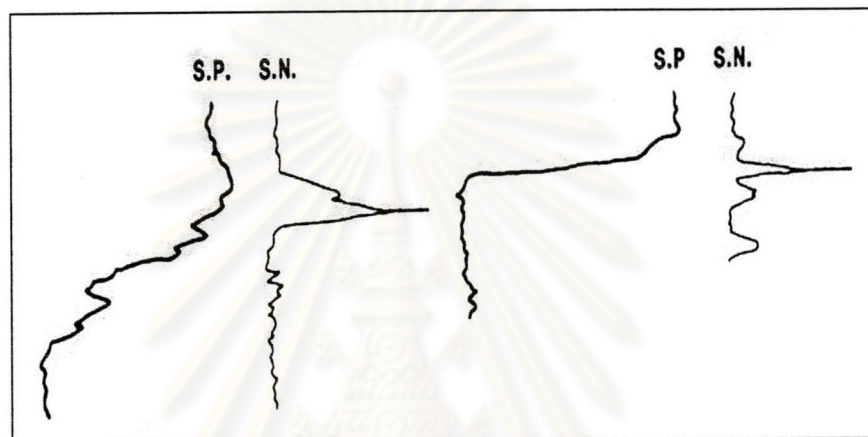

Figure 2.4 The SP curves show transgressive unit environment.

In non-equilibrium conditions, variations from the above idealized curve shapes exist which make identification on a single well difficult. However, examination of equivalent units in a number of wells often yields pattern shapes, which are diagnostic for this particular zone.

2.2 Texture and grain size analysis

The size analysis of sedimentary rocks concerns especially to detrital or clastic rocks. The clastic and detrital rocks results from the transportation of the erosion debris by traction, saltation or suspension into the basin of deposition. Thus, the determination of the size of the particle is of great important in reconstruction the transportation history of the sediment from the source area to the site of deposition

(Babu and Sinkha,1987). The main characteristics of sedimentary particles can be described by determining their size, shape, sorting and composition. Size, shape and sorting define the texture of sediments, but composition is so intimately associated with texture.

2.2.1 Grain size

Fragmental particles constituting sedimentary rock cover a wide range of grain size from boulder to clay size, the handling of such a wide range of grain size is a difficult problem. Udden, 1914 proposed a geometric scale, used to define the grain size distribution is so-called grade scale. Subsequently, in 1922 the various size ranges within the grade scale were named by Wentworth and modified Wentworth grade scale later (Table 2.1). The Wentworth grade scale is provided an appropriate scale for representation of grain size and standardized the sedimentological nomenclature (Sengupta,1994).

2.2.2 Shape

The shape of a sedimentary particle consists of two important attributes, namely, roundness and sphericity. These two attributes of sedimentary particle are very useful in determining the porosity of the reservoir rocks and aquifers. It may also be useful in correlation of sediments.

Roundness may be defined as the sharpness of the corners or the edges, of a grain or lack of it; while sphericity is the ratio existing between length, breadth and thickness. All edges are smooth; roundness coefficient is 100%

The standard visual estimation of sphericity and roundness is developed by Power in 1953 shown in Figure 2.5.

Table 2.1 Grain size classification and nomenclature

Scale (mm.)	WENTWORTH (1922)		Modified WENTWORTH
	Boulder		
256			
	Cobble		
64			
	Pebble		Gravel
4			
2	Granule		
	Sand	Very coarse grained	
1		Coarse grained	
0.5			Sand
		Medium grained	
0.25		Fine grained	
0.125			
0.062		Very fine grained	
	Silt		Silt
0.004			Mud
	Clay		Clay

High sphericity

Low sphericity

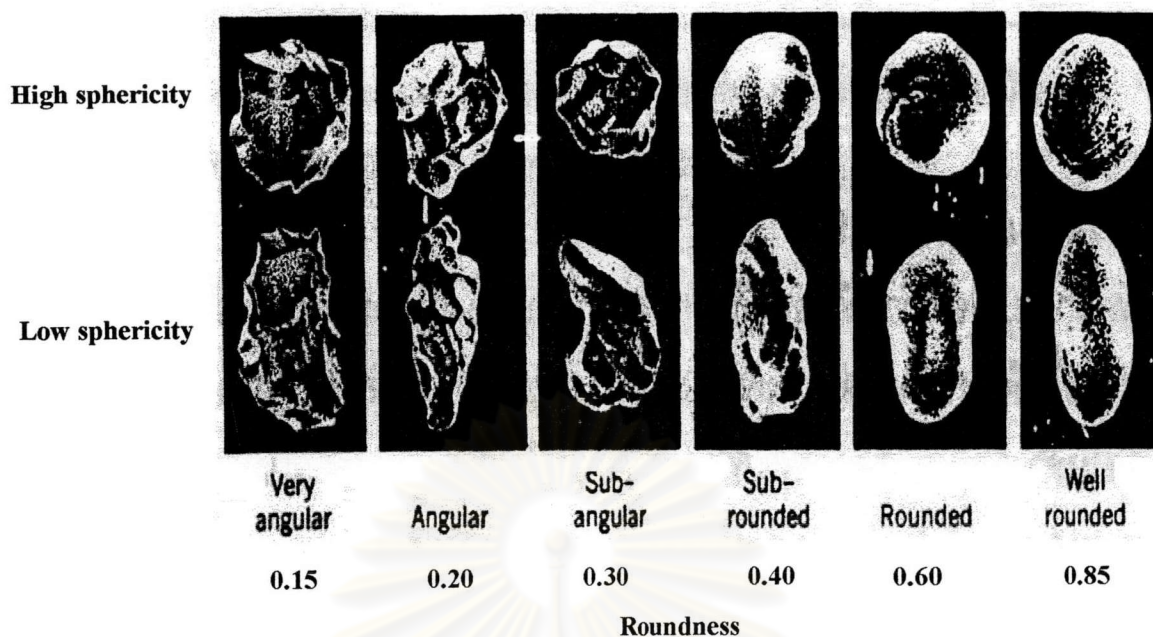| Very angular	Angular	Sub-angular	Sub-rounded	Rounded	Well rounded
0.15	0.20	0.30	0.40	0.60	0.85

Roundness

Fig. 2.5   Visual comparator for estimation two-dimensional roundness of

sand grains. (Power, 1953)

2.2.3 Sorting

Sorting is defined as the measure of the dispersion of the grain-size distribution of sediment. To identify the degree of sorting by counting percent of grained can be divided into 5 classed as follow: 1) very poor sorted, 2) poorly sorted, 3) moderately sorted, 4) well sorted, 5) very well sorted.

2.2.4 Mineral Composition

Mineral composition is a fundamental property of sediment and consequently, its determination becomes exceedingly important. Minerals in sediments can be grouped into two major categories, namely, major minerals and accessory minerals. To describing detrital grains, using hand lens or binocular microscope available in most sedimentology laboratory.

2.3 Hydrochemistry

Groundwater comes from the small percentage of precipitation that falls, infiltrates the ground, traveling downward, and fills the available pore spaces within rock, sand, gravel, and clay. This forms a large subsurface storage area of water that interacts with various rocks, minerals, microorganisms and any manmade or natural materials that may seep from the surface. Any substance that comes in contact with the groundwater can affect water quality.

2.3.1 Important Chemical Constituent Found in Groundwater

Iron

Iron (Fe^{2+}, Fe^{3+}) in groundwater provides the typical well water "rust" taste. Not only is the taste unpleasant, iron can also stain plumbing fixtures, clothes, and dishes. Most groundwater has at least trace amounts of iron because its presence in nature is so common. Iron concentrations exceeding this level may cause the characteristic reddish staining. Iron is generally derived from minerals contained within the underlying bedrock. Limestone, shale, and coal, which often contain the iron-rich mineral pyrite, are large contributors of iron. Like calcium and magnesium; carbonate rocks, acidic rainwater releases iron ions into solution.

Manganese

Manganese resembles iron in its chemical behavior and in its occurrence in natural water, but is less abundant than iron. Manganese is offensive in water in the same general way as iron. It occurs as soluble manganese bicarbonate, which changes to insoluble manganese hydroxide when it reacts with atmospheric oxygen. Stains caused by manganese are more objectionable and harder to remove than those from iron. Manganese bicarbonates precipitate out of solution as a black, sooty deposit when carbon dioxide is liberated from the water near well.

Fluoride

Fluoride normally is present only in small concentrations in groundwater. It may be derived from fluorite (the principal fluoride mineral of igneous rocks) and the minerals apatite and mica. Volcanic or fumarolic gases may also contain fluoride, and in some areas these may be the source of fluoride in water. It is important to know the amount of fluoride in water used by children. Excessive fluoride in the water causes mottling of tooth enamel, which defected to children who drink water containing too high fluoride during the period when permanent teeth are formed; furthermore, teeth may be brittle because fluoride affects tooth density.

Nitrogen

Nitrogen is typically present in ground water in three forms: ammonia (NH_3), nitrate (NO^{3-}), and nitrite (NO_2^{2-}). Of the three, nitrite is the most toxic. Most nitrogen compounds found in the ground water are partially derived from the atmosphere, fertilizers, manure and urine from feedlots and pastures, sewage, and landfills. Nitrates are especially toxic to children less than six months of age known as "blue-baby syndrome". High nitrate concentrations in well water are cause for concern, which there originate from either direct discharge of contaminated surface water into a well or natural infiltration by contaminated surface water.

Sulfur

Sulfur appears in two species, that of sulfide (S^{-2}) and sulfate (SO_4^{-2}). Sulfide is generally in the form of dissolved hydrogen sulfide gas (H_2S). Sulfides originate from areas such as marshes, oil wells, mines, and manure pits. Sulfates are principally derived from the dissolving of minerals such as gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$). Secondary sources of sulfates are from the weathering of pyrite and the dissolving of ammonium sulfate fertilizers. Hydrogen sulfide gives the

characteristic rotten egg smell that is familiar to many people. Sulfides can cause corrosion to plumbing, darken water, and create a foul odor and taste. Sulfates, at high levels, taint the taste of water and may create a laxative effect.

Chloride

Chloride occurs as the predominant negatively ion in seawater. Major source of chloride in sedimentary rock (evaporites); minor sources are igneous rocks. The chloride content of the groundwater found elsewhere averages close to 6 mg/l unless the aquifer have been contaminated with seawater. Where wells near the heavily pumped, some seawater may move into the fresh water aquifer. A running record of the chloride content of water samples from observation wells provides information as to whether contamination of the aquifer may be occurring.

Sodium

Sodium is a metal, one of a group called the alkali metals. Another alkali metal is potassium. While the alkali metals have similar chemical characteristics, sodium is the only one found in significant quantities in natural waters. Sodium derived from rock weathering and carried to the sea is definitely the most abundant metallic ion in seawaters. Sodium does not contribute to the hardness of water. However, groundwaters containing considerable quantities of sodium carbonate or sodium bicarbonate are alkaline and may have pH values of 9 or more.

2.3.2 Important Properties of Water

a) The power of hydrogen ion (pH). Water is said to be either acidic or alkaline, depending on the relative concentration of hydrogen ions. Hydrogen ion in water cause it to act as acid whereas the capability of water to neutralize acid, that is, reduce the number of hydrogen ion in solution, is called alkalinity. The pH range is from 0 to 14, with a pH value of 7 at 25 °C indication a neutral solution in which H^+

and OH⁻ ions have the same concentration. A pH less than 7 indicates an acid solution, while a pH greater than 7 indicates an alkaline solution. Temperature plays a roll in determining the pH at which neutrality occurs. The variation of pH can be identified as follow: very high pH values, that is above 8.5, are usually associated with sodium-carbonate-bicarbonate waters, moderately high pH values are commonly associated with water high in bicarbonate, very low pH values, that is below 4.0, are associated with water containing free acid derived from oxidizing sulfide minerals, usually pyrite, or from waters in contact with volcanic gases containing hydrogen sulfide, hydrochloric acid, and other volatiles and moderately low pH values may be associated with small amounts of mineral acids from sulfide sources or with organic acid from decaying vegetation (Davis and Dewiest, 1966).

b) Specific Electrical Conductance (EC). Specific electrical conductance or Electrical Conductivity is defined as the conductance of a cubic centimeter of any substance compared with the conductance of the same volume of water. Values of specific conductance for groundwater are reported in millionths of mhos (micromhos) [microsiemens (μS) in the SI system]. The specific conductance readings are usually adjusted to 25 °C, the variations in conductance are a function of the concentration and type of dissolved constituents present. The common types of natural water, calcium bicarbonate and calcium sulfate water generally have the lowest conductance and sodium chloride water the highest conductance for a given total dissolved solids. Pure water has a conductance of 0.55 micromhos at 25 °C, laboratory distilled water commonly has a conductance of 0.5 to 5.0 micromhos. Rainwater will usually range from about 5.0 to 30 micromhos, potable subsurface water ranges from 30 to 2,000 micromhos, ocean water from 45,000 to 55,000

micromhos, and oil-field brines are commonly more than 100,000 micromhos (Davis and Dewiest, 1966).

c) Hardness

Hardness is defined as water that is rich in calcium (Ca^{2+}) and/or magnesium (Mg^{2+}). Hard water generally causes the formation of soap curd in pipes, sinks, and bathtubs. Calcium may precipitate as calcium carbonate within the plumbing and clog pipes. Calcium and Magnesium are primarily found in ground water due to the dissolving of limestone (primarily composed of calcium carbonates). The dissolving of limestone occurs when the limestone reacts with rainwater, which has become slightly acidic through a reaction with carbon dioxide. Calcium and Magnesium ions are also released when the water reacts with naturally occurring gypsum. The degree of hardness in water is commonly based on the classification listed in Table 2.2

Table 2.2 Hardness Classification of Water (Sawyer and McCarty, 1967)

Hardness, mg/l as CaCO$_3$	Water Class
0-75	Soft
75-150	Moderately hard
150-300	Hard
Over 300	Very hard

d) Total Dissolved Solids

Total dissolved solids (TDS), is defined as the concentration of all dissolved minerals in the water. TDS are a direct measurement of the interaction between groundwater and subsurface minerals. High TDS, greater than 1000 mg/L, is commonly offensive to taste. TDS levels over 2000 mg/L are generally considered undrinkable due to strongly offensive taste. A higher concentration of TDS usually

serves as no health threat to humans until the values exceed 10,000 mg/L. At this level the water is considered saline water and defined as undrinkable. A high TDS (levels above 1,000 mg/L) may cause corrosion of pipes and plumbing systems. Table 2.3 presents a groundwater classification system based on total dissolved solids (Freeze and Cherry, 1979).

Table 2.3 Simple groundwater classification based on Total Dissolved Solids

Category	Total Dissolved Solids (mg/l)
Fresh water	0-1,000
Brackish water	1,000-10,000
Saline water	10,000-100,000
Brine water	More than 100,000

2.3.3 Groundwater Types

The major ion composition of groundwater is used to classify groundwater into various types based on the dominant cations and anion. The composition of the dominant ions can be displayed graphically by several methods which one of the most useful summary presentations is the Piper Trilinear Diagram.

2.3.3.1 Piper Trilinear Diagram

The trilinear diagram, developed by Piper in 1944, considers the cation (positively charges ions) and anions (negatively charged ions) as two separate groups. The major cation viz. Calcium (Ca^{2+}), Manganese (Mg^{2+}), Sodium (Na^+), Potassium (K^+), are grouped together and the major anions viz. Sulfate (SO_4^{2-}), Chloride (Cl^-), Bicarbonate (HCO_3^-), Carbonate (CO_3^{2-}) are grouped together. The concentrations of the cations and anions are considered in quivalents per million (epm). So, the relative concentrations of the chemical species are used to determine the dominant ions.

These two groups of ions in each water sample are plotted in separate triangular fields as two points and these two points are projected into the central diamond shaped field parallel to the sides of the triangles and the meeting point is marked. This point represents the water type and the zone in which this point falls in the diamond shaped field as well as in the two triangular fields determine the water type (Fig 2.6). The interpretation of water quality are explained from Palmer's classification (Palmer, 1911) as follows:
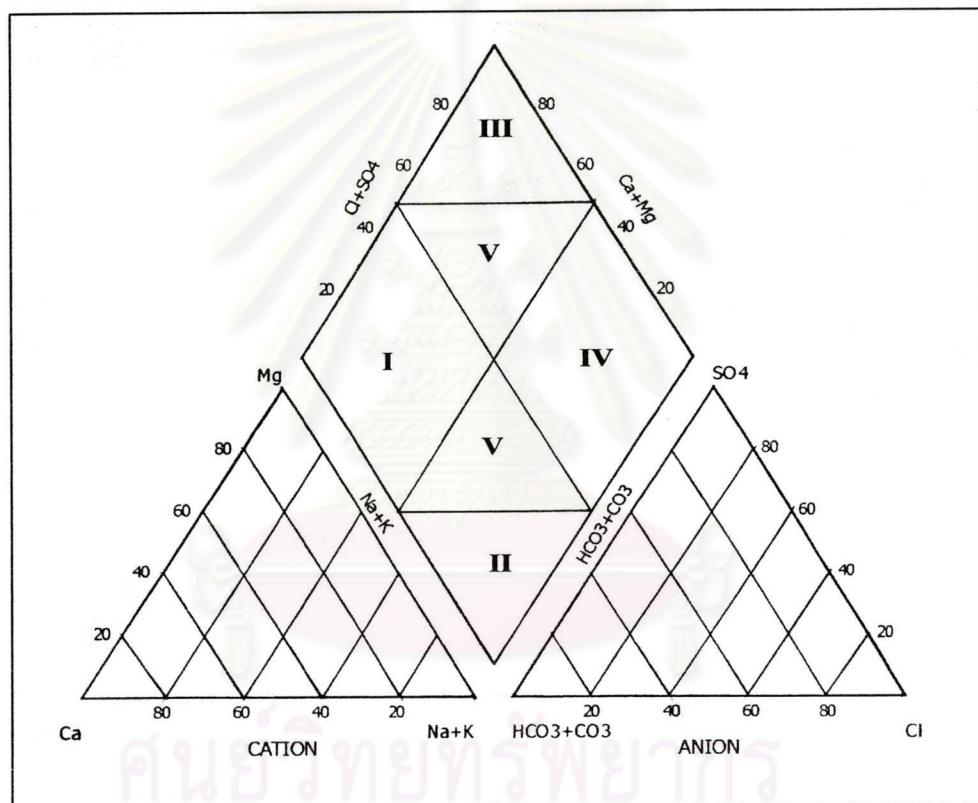

Figure 2.6 Schematic of plotting the diamond – shaped field

Type I: carbonate hardness exceeds 50 percent-that is, chemical properties of the groundwater are dominated by alkaline earth and weak acids. This area is called "Carbonate Hardness Facies" or "Hydrochemical Facies type I" (Ca + Mg, $HCO_3+CO_3 > 50\%$). Its properties are temporary hardness and fresh water.

Type II: carbonate alkali exceeds 50 percent - that is, chemical properties of the groundwater are dominated by alkali and weak acid. The groundwater plotted in this area are inordinately soft in proportion to their content of dissolved solids (Piper,1944). This area is called "Carbonate Alkali Facies" or "Hydrochemical Facies type II" (Na+K, HCO_3+CO_3 >50%). Its properties are soft and fresh water.

Type III: noncarbonate hardness exceeds 50 percent-that is, chemical properties of the groundwater are dominated by alkali-earth and strong acid (Piper,1944). This area is called "Noncarbonate hardness Facies" or "Hydrochemical Facies type III" (Ca+Mg, Cl + SO_4 > 50%). Its property is hard water.

Type IV: noncarbonate alkali exceeds 50 percent-that is, chemical properties of the groundwater are dominated by alkali and strong acids; ocean water and many brines plot in this area, (Piper,1944). This area is called "Noncarbonate Alkali Facies" or "Hydrochemical Facies type IV" (Na+K, Cl + SO_4 > 50%). Its property is brackish to salty water.

Type V: mixing water-that is, chemical properties of the groundwater are neither cation nor anion dominated. They are mixing together and their property is not soft or hard water cannot be specified.

2.3.3.2 Drinking Water Standards

The purpose of a water analysis is to determine the suitability of water for a proposed use. Most drinking water supplies in Thailand conform to the GROUNDWATER ACTS B.E. 2520 (in Thai) established by The Department of Mineral Resources. A summary of the principal provisions relating to quantitative limits is given in table 2. 4

Table 2.4 Standard of Groundwater Quality, GROUNDWATER ACTS B.E. 2520

Physical Characteristics		
Criterion	**Maximum Acceptable Limit**	**Maximum Allowable Limit**
Color	5 (Platinum-cobalt)	50 (Platinum-cobalt)
Turbidity	5 (Units)	20 (Units)
PH	7.0-8.5	6.5-9.2
Chemical Characteristics		
Criterion	**Maximum Acceptable Limit (ppm.)**	**Maximum Allowable Limit (ppm.)**
Iron (Fe)	0.5	1.0
Mangnanese (Mn)	0.3	0.5
Copper (Cu)	1.0	1.5
Zinc (Zn)	5.0	15.0
Sulphate (SO_4)	200	250
Chloride (Cl)	200	600
Fluoride (F)	1.0	1.5
Nitrate (NO_3)	45	45
Total hardness as $CaCO_3$	300	500
Non-carbonate hardness as $CaCO_3$	200	250
Total solids	750	1,500
Toxic Characteristics		
Criterion	**Maximum Acceptable Limit (ppm.)**	**Maximum Allowable Limit (ppm.)**
Arsenic (As)	-	0.05
Cyanide (CN)	-	0.2
Lead (Pb)	-	0.05
Mercury (Hg)	-	0.001
Cadmium (Cd)	-	0.01
Selenium (Se)	-	0.01
Biological Characteristics	
Criterion	**Maximum Acceptable Limit**
Standard plate count	Not more than 500 colonies per cubic centimeters
Most probable number of coliform organism (MPN)	Less than 2.2 per 100 cubic centimeters
E. coli	-

2.4 Pumping Test

In groundwater hydrology, the important factors are the quality and quantity of water that can be developed from wells. The quality of water can be easily determined by chemical analyses, but the quantity of water in underground storage is not so easy to determine because it is invisible. In order to solve this problem, several methods of prediction and calculation are used. A pumping test is one of methods that chosen to study the hydrogeology.

A pumping test is a quantitative study to determine:

1) The performance characteristics of a well, well production test, yield and drawdowns are recorded so as to calculate the specific capacity and the productive capacity of the completed well.

2) The hydraulic parameters of the aquifer, aquifer test, transmissivity and storativity can be calculated. This type of test is especially important because they define the hydraulic characteristics of a water bearing formation. The tranmissivity indicates how much water will move through the formation, and the storativity indicates how much water can be removed by pumping and draining.

The well production test and aquifer test comprise the static water level just before the test is started, time since the pumping start, pumping rate, pumping level or dynamic water levels at various intervals during the pumping period, time of any change in discharge rate, and time the pump stopped. Measurements of water levels after the pump is stopped (recovery) are extremely valuable in verifying the aquifer coefficients calculated during the pumping phase of the test.

2.4.1 Hydraulic Parameters

It is important to understand clearly the meaning of common terms related to pumping wells. Definitions are presented as below:

Static Water Level (SWL) - This is the level at which water stand in a well or unconfined aquifer when no water is being removed from the aquifer either by pumping or free flow.

Pumping Water Level (PWL) – This is the level at which water stands in a well when pumping is in progress.

Drawdown – Drawdown is the difference, measure in feet or meters, between the water table or potentiometric surface and the pumping water level.

Residual Drawdown – After pumping is stopped, the water level rises and approaches the static water level observed before pumping began. During water–level recovery, the distance between the water level and the initial static water level is called residual drawdown.

Well Yield – Yield is the volume of water per unit of time discharged from a well, either by pumping or free flow. It is measured commonly as a pumping rate in gallons per minute or cubic meters per day.

Specific Capacity – Specific capacity of a well is its yield per unit of drawdown, usually expressed as gallon of water per minute per foot (gpm/ft) of drawdown or cubic meters per day per meter (m^3/day/m) of drawdown, after a given time has elapsed, usually 24 hours. Dividing the yield of a well by the drawdown, when each is measured at the same time, gives the specific capacity.

Hydraulic Conductivity (K) - Hydraulic conductivity indicates the quantity of water that will flow through a unit cross- sectional area of a porous medium per unit time under a hydraulic gradient of 1 unit at a specified temperature.

Transmissivity (T) – Defining it as the rate of flow in gallons per minute through the vertical section of an aquifer one foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of 1.

Storativity (S) – The storativity of a saturated of thickness confined aquifer can be defined as the volume of water that an aquifer release from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface.

2.4.2 Basic Theory of Pumping Test

2.4.2.1 Equilibrium Well Equations

In 1906, Thiem, developed Darcy's basic flow equation to ground water flow toward a pumping well which objective was to derive simple mathematical expressions for describing the flow regime of water in the ground. There are two basic equations: one for unconfined conditions and the other for confined conditions. For both equations, all dynamic conditions in the well and ground are assumed to be in equilibrium; that is, the discharge is constant, the drawdown and radius of influence have stabilized, and water enters the well in equal volumes from all directions. Both assume horizontal flow everywhere in the aquifer with recharge occurring at the periphery of the cone of depression The Thiem equation of an unconfined aquifer can be written as:

$$Q = \frac{1.366 \, K \, (H^2 - h^2)}{\log R/r} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.1$$

Where

Q = Well yield or pumping rate, in m^3/day

K = Hydraulic conductivity of the water bearing formation, in m/day

H = Static head measured from bottom of aquifer, in m.

h = Depth of water in the well while pumping, in m

The equation for a well operating under confined aquifer is:

$$Q = \frac{2.73Kb(H-h)}{\log R/r} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.2$$

Where

> b = thickness of aquifer, in m

> All other terms are as defined for equation (2.1)

Derivations of the equation are based on

1. The water-bearing materials have a uniform hydraulic conductivity within the radius of influence of the well.

2. The aquifer is not stratified

3. For an unconfined aquifer, the saturated thickness is constant before pumping starts; for a confined aquifer, the thickness is constant.

4. The pumping well is 100% efficient, that is, the drawdown levels inside and just outside the well bore are at the same elevation.

5. The intake portion of the well penetrates the entire aquifer.

6. The water table or potentiometric surface has no slope

7. Laminar flow exists throughout the aquifer and within the radius of influence of the well.

8. The cone of depression has reached equilibrium so that both drawdown and radius of influence of the well do not change with continued pumping at a given rate.

9. A serious limitation of this formula is the fact that equilibrium or steady flow conditions must be reached before the formula can be applicable. To remove this restriction, Theis (1935) developed the non-equilibrium equation.

2.4.2.2 Nonequilibrium Well Equation

Theis developed the nonequilibrium well equation in 1935. The Theis equation was the first to take into account the effect of pumping time on well yield. Its derivation was a major advance in groundwater hydraulics.

$$s = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \ldots\ldots\ldots\ldots\right] \quad \ldots\ldots\ldots 2.3$$

Where

s = Drawdown, in m, at any point in the vicinity of a well discharging at a constant rate

Q = Pumping rate, in m^3/day

T = Transmissivity of the aquifer, m^2/day

$$u = \frac{r^2 S}{4Tt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots2.3a$$

Where

r = Distance, in m, from the center of a pumped well to a point where the drawdown is measured

S = Storativity (dimensionless)

T = Transmissivity of the aquifer, m^2/day

t = Time since pumping started, in days

Derivation of the Theis equation is based on the following assumptions:

1. The water – bearing formation is uniform in character and the hydraulics conductivity is the same in all directions.

2. The formation is uniform in thickness and infinite in areal extent.

3. The formation receives no recharge from any source.

4. The pumped well penetrates, and receives water from, the full thickness of the water – bearing formation.

5. The water removed from storage is discharged instantaneously when the head is lowered.

6. The pumping well is 100% efficient.

7. All water table removed from the well comes from aquifer storage.

8. Laminar flow exists throughout the well and aquifer.

9. The water table or potentiometric surface has no slope.

These assumptions are essentially the same as those for the equilibrium equation except that the water levels within the cone of depression need not have stabilized or reached equilibrium.

2.4.2.3 Modified Nonequilibrium Equation

In working with the Thies equation, Cooper and Jacob, 1946 recognized that the sum of the terms beyond ln u (equation 2.3) is not significant when u becomes small. The value of u decreases as the time, t increases and r decreases. Therefore, the nonequilibrium equation can be modified to the following form without significant error (Driscoll, 1986):

$$s = \frac{0.183Q}{T} \, Log \, \frac{2.25Tt}{r^2S} \qquad \text{....................................2.4}$$

Where

s = Drawdown, in m, at any point in the vicinity of a well discharging at a constant rate

Q = Pumping rate, in m^3/day

T = Transmissivity of the aquifer, m^2/day

r = Distance, in m, from the center of a pumped well to a point where the drawdown is measured

S = Storativity (dimensionless)

t = Time since pumping started, in days

Where the symbols represent the same terms as in Equation 2.3 and 2.3a. Equation 2.4 is similar in form to the Theis equation except that the exponential

integral function, $W(u)$, has been replaced by a logarithmic term which is easier to work with in practical applications of well hydraulics.

By using these simplified relationships based on Equation 2.4, it is possible to derive information on the hydraulic characteristics of the aquifer by plotting drawdown and time data taken during a pumping test. The data are plotted on semi logarithmic paper. Applying the first of the relationships developed above, time, t, is plotted horizontally on the logarithmic scale; drawdown , s, is plotted vertically on the linear scale. All the points except those representing measurements made during the first 10 minutes of pumping fit the line. During the first 10 minutes, the value of u is larger than 0.05 and so the modified nonequilibrium equation is not applicable within that phase of the test.

The transmissivity is calculated from the pumping rate and the slope of the time – drawdown graph by using the following relationship developed from Equation 2.4

$$T = \frac{0.183Q}{\Delta s} \quad\quad\quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots2.5$$

Where

T = Transmissivity of the aquifer, m^2/day

Q = Pumping rate, in m^3/day

Δs = Slope of the time – drawdown graph expressed as the change in drawdown between any two times on the log scale whose ratio is 10 (one log cycle)

The storativity is also readily calculated from the time–drawdown graph by using the zero– drawdown intercept of the straight line as one of the terms in equation.

$$S \quad = \quad \frac{2.25Tt_0}{r^2} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.6$$

Where

S = Storativity (dimentionless)

T = Transmissivity of the aquifer, m^2/day

t_0 = Pumping rate, in m^3/day

r = Distance, in m, from the pumped well to the observation well where the drawdown measurement were made

It is a good practice to pump a well in a confined aquifer for 24 hours to get data for the time–drawdown curve. A well in unconfined aquifer should be pumped for 3 days. The 240 minutes pumping period is too short for most situations. A longer test provides data that define more reliably the slope and position of the line of best fit for the plotted points.
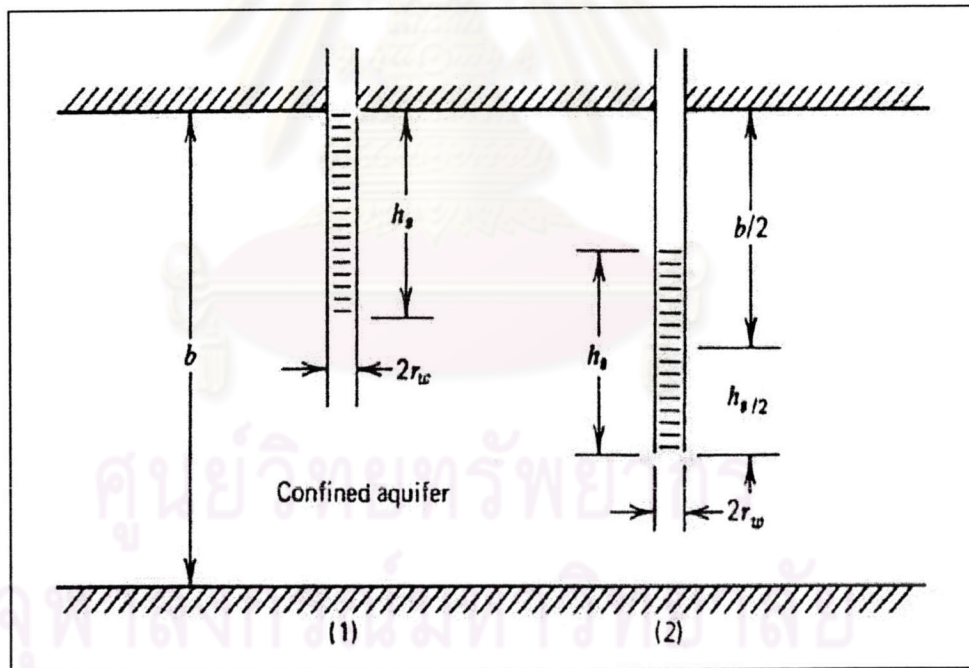
2.4.2.4 Partially Penetrating Well

A well which length of water screen penetrated is less than the aquifer, it is known as a partially penetrating well (Todd, 1980) as shown in figure 2.7, which illustrates the situation of partially penetrating well in a confined aquifer.

The flow pattern to such wells differs from the radial horizontal flow assumed to exist around fully penetrating wells. The average length of a flow line into a partially penetrating well exceeds that into a fully penetrating well so a greater resistance to flow is thus encountered. The drawdown s_p at the well face of a partially penetrating well in a confined aquifer (Fig 2.7a) can be expressed as
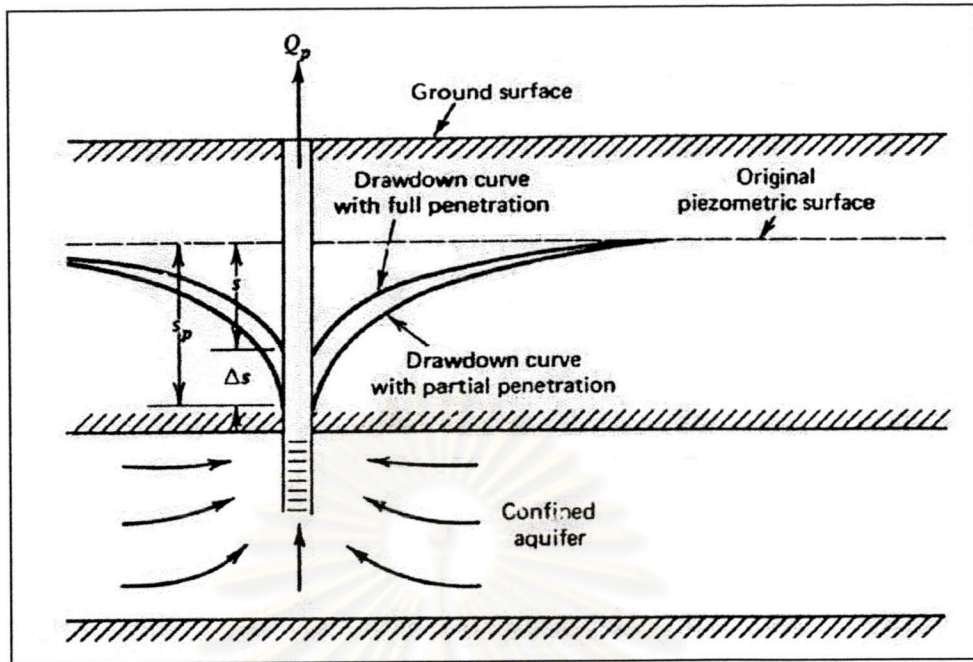
(a)

(b)

Figure 2.7 Partially penetrating wells in a confined aquifer. (a) Effect of partially penetrating well on drawdown. (b) Two configurations of partially penetrating wells

$$s_p = s + \Delta s \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots2.7$$

Where Δs refers to the additional drawdown resulting from the effect of partial penetration. It can be shown for steady–state conditions and the typical situation in Fig 2.7b(1)

$$\Delta s = \frac{Q_p}{2\pi T} \frac{1-p}{p} \ln \frac{(1-p)hs}{rw} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots2.8$$

Where T is Transmissivity, p is the penetration fraction ($p = hs / b$) and hs and rw are shown in fig. 2.7b(1) Equation (2.7) applies where $p > 0.2$

For the case of a well screen centered in the thickness of the aquifer fig 2.7b(2) the value of s is given by

$$\Delta s = \frac{Q_p}{2\pi T} \frac{1-p}{p} \ln \frac{(1-p)hs}{2rw} \quad\ldots\ldots\ldots\ldots\ldots2.9$$

Equation 2.9 can be modified for a well in an unconfined aquifer by definition

$$\Delta s\, 2hw = \frac{Q_p}{\pi K} \frac{1-p}{p} \ln \frac{(1-p)hs}{rw} \quad\ldots\ldots\ldots\ldots\ldots2.10$$

Where hw is the saturated thickness at the well with full penetration and the hydraulic conductivity $K = T/hw$.

Then

$$s_p^2 = s^2 + \Delta s\, 2hw \quad\ldots\ldots\ldots\ldots\ldots\ldots2.$$

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In case of an observation well is located more then 1.5 to 2 time the saturated aquifer thickness from a pumping well, the effect of partial penetration can be neglected for homogeneous and isotropic aquifer

2.4.2.5 Water Level Recovery Data

When pumping is stopped, well and aquifer water levels rise toward their pre-pumping levels. The rate of recovery provides a means for calculating the transmissivity and storativity. The time–recovery record, therefore, is an important part of an aquifer test. The time–drawdown measurements taken during the pumping period and the time–recovery measurements taken during the recovery period provide two different sets of information from a single aquifer test. Values obtained from analysis of the recovery record serve to check calculations based on the pumping record. The transmissivity can be calculated from the recovery test as the equation 2.12

$$T = \frac{0.183Q}{\Delta s'} \quad \text{...2.12}$$

Where

$\Delta s'$ = The resdidual drawdown

2.4.6 Specific Capacity; SC

The specific capacity is the ratio of pumping rate to the drawdown estimated during well development. The specific capacity is most useful in deciding the relative values of transmissivity where no other information existed. The specific capacity values are varies which depending on the type of screen, screening section, and completeness of the development.

According to the result of pumping test of each well, specific capacity of well yield can be calculated by using formula

$$SC = \frac{Q}{DD} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.13$$

Where

SC = Specific capacity of well yield in m³/day per m. of drawdown

Q = Water discharge in m³/day

DD = Drawdown in m.

2.5 Flow Nets Analysis

The flow nets are a graphical solution to the Laplace equation that can be used to determine quantity of water flowing through area

$$\frac{\partial^2 h}{\partial X} + \frac{\partial^2 h}{\partial Y} = 0 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.14$$

For two–dimensional seepage can be presented as flow nets. Two orthogonal sets of curves form a flow net: equipotential lines are line of constant total head which connected points of equal total head (h), flow lines represent the paths that water would flow which indicating the direction of seepage down a hydraulic gradient.

Rules for construction flow nets:

1. Flow always occurs in the direction of maximum drop in total head. Therefore, flow lines and equipotential lines should intersect at 90° angles (Fig 2.8).

2. Cells formed by the flow lines and equipotential lines should have a uniform length to width ratio. If draw the flow net such that each of the squares has the same width to length ratio (l/b = constant). It will have the same of flow in each flow channel and all of the equipotential drops will be equal (Fig 2.9).
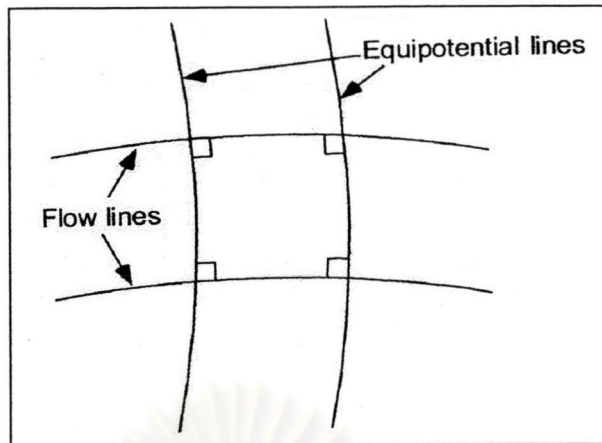
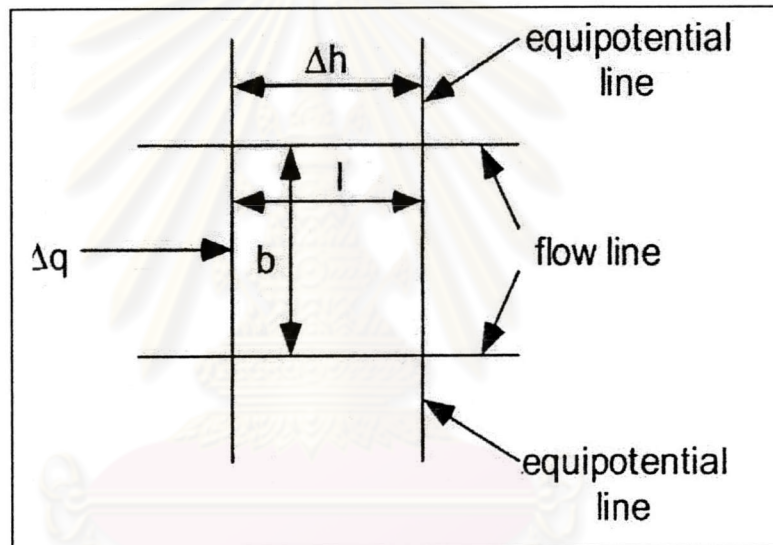Fig 2.8 Flow lines and equipotential lines intersect at 90° angles

Fig 2.9   Cells formed by the flow lines and equipotential lines for one channel

have a uniform length to width ratio

Flow net construction is easier if $l/b = 1$. Sometimes placing circle in the cell helps to ensure that $l/b = 1$.

For one flow channel:

$$\Delta q = \frac{k\Delta h\, l}{b} \quad \dots\dots\dots\dots\dots\dots\dots2.15$$

$$\Delta h = \frac{h\ total}{\#\ of\ drops} = \frac{h}{ne} \quad \dots\dots\dots\dots\dots\dots\dots2.16$$

Where

h total = total head loss through region

ne = number of equipotential drops

$$\Delta q = \frac{Kh/neb}{l} \quad \dots\dots\dots\dots\dots\dots\dots2.17$$

For all flow channels

$$\Delta q = \frac{nf\,\Delta q}{l} = \frac{knfbh}{nel} \quad \dots\dots\dots\dots\dots\dots\dots2.18$$

Where

nf = number of flow channels

Q = total flow through all channels

If b = 1 (square elements)

$$Q = \frac{K\,nf\,h}{ne} \quad \dots\dots\dots\dots\dots\dots\dots2.19$$

2.6 Previous Works

Piancharoen and Chuamthaisong (1976) studied the groundwater wells in Bangkok Metropolis. They pointed out that thick sequence of sediments overlying the basement complex in the Chao Phraya Basin was unconsolidated and semi-consolidated sediments ranging in age from Tertiary to Quaternary. At least three major breaks of deposits were recognized and each break could be also subdivided into minor horizons. The topmost formation is of marine, soft to stiff, dark gray to black clay with the thickness ranging form 20-30 meters. Underlying the marine clay to the first break at the depth off about 100 meters are two sequences of medium to coarse sand and gravel layers with minor clay lenses. The second break is found at 250 meters depth in the northern part of Bangkok and gradually increases in depth to 400 meters near the Gulf. The sediment at the depth of 100 to 400 meters appears to have more or less the same characteristics the overlying formation. The distinct break at the depth of 350 to 400 meters suggested that the whole deposits were probably accumulated under subaerated fluviatile environment during the lower-middle Pleistocene. Beneath the second break, the deposits consist mostly of well sorted, medium to coarse sand with occasional gravel. These deposits might be corresponding to the sedimentary facies of shaly sand, dark shale and red beds deposits in the fluviatile-fluviomarine environments penetrating in the Gulf of Thailand which deposited during the sea transgressed in Pliocene (Woollands and Haw, 1976)

Piyasena (1979) did a thoroughly analysis of lithologic of groundwater wells in Bangkok area by the systematic correlation procedure and delineated the stratigraphy of Bangkok subsoils. He found that the Bangkok subsurface consisted of alternative sand and clay layers and identified three partially separated sand layers.

Jitapunkul (1980) studied the sedimentary facies and groundwater potential of some Quaternary deposits in Bangkok area by the borehole investigation. He concluded that the 250 meters thick of sand/mud sequences are identified in terms of sedimentary facies as fluvial mud, shelf mud, deltaic plain and delta front of the upper delta cycle and deltaic plain of the lower delta cycle irrespective to the increasing depth. The uppermost facies is a thin veneer fluvial mud overlying the shelf mud facies of varying thickness from 10 to 20 meters. These two facies are believed to be deposited during the Holocene Epoch. Underlying the Holocene sediments are the alternating sandy and muddy sequences of deltaic plain facies and delta front facies of the upper delta cycle of approximately 90-180 meters thick. The lower boundary of the upper delta cycle is marked by the break of deposition. The lowest part of the whole sequences under the present investigation is the alternating sandy and muddy sediments of deltaic plain facies of the lower delta cycle. The two delta cycles are believed to be deposited during the Pleistocene Epoch. Lithological analysis of the sedimentary sequences reveals that there are four distinctive sand bodies with extensive aerial extent of considerable thickness. These are the aquifers which interbedded with the muddy sediments that were deposited in various sediments and the geometry of these aquifers vary considerably with apparent evidence of the interconnection up to the certain extent.

Chuamthaisong and Yuthamanop (1982) worked on the relative age dating of groundwater and the velocity of groundwater flow in Bangkok area and its vicinity and locating the recharge areas of the aquifers. They used the environmental isotope techniques for this study. They concluded that the upper three aquifers received the recharge from the same sources and/or they were hydraulically interconnected due to

leakage through aquifer boundaries. They also found that the occurrence of groundwater was partly directed to recharge area in the vicinity of Bangkok.

Asian Institute of Technology (AIT) and Department of Mineral Resources (DMR) (1982) submitted a comprehensive report on the groundwater resource in Bangkok area. They compiled the information existed on hydrogeology and conducted preliminary analysis of the dynamic behavior of Pra Pradaeng, Nakhon Luang, and Nonthaburi aquifers. A monitoring network was installed for observing water level and pumping tests were conducted to supplement the information on aquifer characteristics. They also did a water balance study and found that the estimated groundwater recharge for the Lower Chao Phraya Basin was 3% of the annual rainfall. A mathematical model was formulated and applied for predicting the behavior of the aquifer system under different schemes of groundwater development.

Thiramongkol (1983) published his research result on geomorphology of the Lower Central Plain, Thailand. The study was based on the interpretation of landsat imagery, topographic map of a scale 1:50,000 and fieldwork. The landforms were classified into 14 units. Fan and terrace occupied marginal zones of the plain. A peneplain and structural terrace in the eastern part of the plain are oldest landforms of the region. A delta of fluviatile sediments occur a broad plain between areas in the northern part of plain. Delta of brackish water sediments occurs in the middle part of Lower Central Plain and along the Chao Phraya River. Tidal flat of brackish water clay, tidal flat of marine clay and tidal zone occur along the shoreline of the Lower Central Plain. Barrier beaches occur in the Lower Central Plain, one in the south and one in the southeast. And floodplain, are up to 15 km. Wide along big river but form narrow ones along small rivers.

Ramnarong (1983) discussed the environmental impacts of heavy groundwater development in Bangkok. She explained the problems of groundwater depletion and quality degradation of aquifers in Bangkok. She pointed that the center of land subsidence was in the east-southeast areas of Bangkok and problems of flood and submergence occurred in some part of the city since the ground elevation ranged from 0.5 to 2.0 meters above mean sea level only.

Buapeng (1990) discussed the use of environmental isotopes on groundwater hydrology in selected areas of Thailand. Special attention was given to Bangkok Metropolitan area. Groundwater was sampled for isotopic and chemical analyses. She concluded that the recharge areas of the Bangkok aquifers could be considered at the area north of Phra Nakhon Si Ayutthaya province up to the northern boundary of the Lower Chao Phraya Basin. It was confirmed that the groundwater in the Bangkok aquifers were of old ages and there was no direct recharge to the aquifers in the Bangkok Metropolitan area. Seawater intrusion in the aquifers was found only in the areas near the Gulf of Thailand.

Fuangswadi (1991) studied the hydrochemistry of groundwater in Bangkok and its vicinity. She analyzed the hydrochemical data of the monitoring wells by statistical, hydrochemical, and groundwater modeling methods. She concluded that there were different types of groundwater in the aquifers but of the same age. She studied the hydrochemistry of groundwater by Piper and expanded Durov diagrams and found out some water types in the eastern area of Bangkok.

Ramnarong (1991) discussed the groundwater quality monitoring and management activities in Thailand. She gave a detailed note of the groundwater quality deterioration in Thailand and the saltwater intrusion problem in Bangkok Multi-Aquifer System. She also discussed the monitoring and management activities

in Thailand and in Bangkok. She presented the details of the groundwater-monitoring network in Bangkok briefly.

Department of Mineral Resource (1992) published the report of the details of groundwater monitoring network and data in Bangkok and its adjacent provinces. The report included the details of the monitoring network, surface benchmarks, well technical records, and the chemical analyses data of groundwater in three principal aquifers as available till that time. It also gave an elaborate discussion of the well logs, and lithology of each monitoring station.

Ramnarong and Buapeng (1992) discussed the impact and management of the groundwater resources of the Bangkok and its vicinity. They pointed out that the remedial measures for controlling groundwater pumpage introduced in 1983 were useful and a continuous recovery of piezometric level was observed in central Bangkok and its eastern suburbs, which led to the decreasing rate of land subsidence. They also noted that in the outskirts of Bangkok where groundwater was increasingly developed, the land subsidence rates increased.

Japan International Cooperation Agency (JICA) (1995) published the final main report of their study on the management of groundwater and land subsidence in Bangkok Metropolitan area and its vicinity. They analyzed the data from the monitoring wells of the Department of Mineral Resource. The chemical analyses of groundwater showed very high chloride concentration in Samuth Sakhon to Pathum Thani provinces along the Chao Phraya River and in the coastal areas of Samut Prakan province. High chloride concentrations ranging from 3,000 to 16,000 mg/l were observed in the main aquifer. The study shown that the groundwater level is again lowering because of the effect of the regional decline of groundwater level

caused by overpumping in the vicinity, e.g., Lat Krabang, Pathum Thani and Samut Sakhon.

2.7 History of Groundwater Usage

It is believed that groundwater from deep wells has been used by various government agencies for domestic and drinking purposes in Bangkok since 1907. Private sector also started to use groundwater in the same period but only from shallow wells. In 1954, the Metropolitan Water Works Authority began to use and supply groundwater to the municipality at an initial rate of 8,360 m^3/day, due to inadequacy of surface water. In 1974, the demand on groundwater for the Authority was increased to 370,000 m^3/day, and to 447,000 m^3/day in 1982. In 1982 alone, 944,000 m^3/day of groundwater was used by private sector for real estates, industrial plants and hotels in Bangkok. Total groundwater consumption in that year was found as high as 1.4 million m^3/day. In 1992 groundwater pumping was estimated from the well inventory database at 1,480,000 m^3/day.

2.7.1 Groundwater Situation

One of obvious problems of the Bangkok area is the decline of static water level because of withdrawal of groundwater continuously for many decades. During 1958-1959, the average water level in the Nakorn Luang aquifer in Bangkok was 4-12 m. below the ground surface. By comparison, it decreased to 24-48 m. in 1988. The Phra Pradaeng aquifer, underlying Amphoe Phra Pradaeng, Samut Prakan Province, the water level changed from 18 m., in 1969, to 40 m. in 1988.

Recently, the decreasing of water level is higher in the vicinity of Bangkok than in the inner city because the Water Work Authority could not supply sufficient

water. Thus, the pumping of groundwater in the vicinity area is excessively increasing.

2.7.2 Effects of Overpumping

Water level in the Nakorn Luang and Nonthaburi aquifers have decreased considerably more than the Phra Pradaeng aquifer because of their better groundwater quality. In Samut Prakan and Samut Sakhon Provinces, the water pumping is also high because a lot of industrial factories are located in that area. As the more groundwater overpumping continue, the saltier in water quality of the Phra Pradaeng aquifer increasing. This makes the others two adjacent aquifers becoming more and more exploited. The overextraction of groundwater caused the potentiometric surface decreasing rapidly. The effected damage from this phenomenon is the pump has to be replaced and/or improved to have higher capacity, inducing saltwater intrusion from the sea into the fresh water aquifer and causing the land subsidence.