WESTERN PACIFIC EARTH SCIENCES
Vol.1, No.4, P.459-472, 7 Figs., 1Tab., November, 2001

IMPLICATION OF SEAWATER INTRUSION ON THE DELINEATION OF THE HYDROGEOLOGIC FRAMEWORK OF THE SHALLOW PINGTUNG PLAIN AQUIFER

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ABSTRACT

Seawater intrusion along the Pingtung coast area provides an excellent opportunity to reexamine the regional hydrogeologic framework especially along the coast. The average width of the mixing zone, 1000 to 10000 mg/l of total dissolved solids (TDS), in the Central Geological Survey CGS aquifer 1 and 3 ranges from 2 to 2.5 km respectively while the average width of the mixing zone of the CGS aquifer 2 is about 5 km in general. This distinctive vertical TDS distribution provides some natural constraints on the hydrogeologic framework particularly along the coast. The presence of a confining layer at the depth of 60 -130 m below the mean sea level in the alternative hydrogeologic framework, two aquifers with one confining layer, for the shallow Pingtung plain matches this vertical TDS discrepancy. This delineation of the regional hydrogeologic framework not only provides a possible answer to the difference of the size of the TDS mixing zone vertically but also accounts for the groundwater level fluctuations in the area.

Key words: hydrogeologic framework, seawater intrusion

INTRODUCTION

A competent conceptual hydrogeologic framework is the foundation of regional hydrogeology study and water resource management. It serves primarily as a basis for describing the regional geologic and hydrogeologic units, delineating boundaries of aquifers and confining units, describing groundwater flow system and hydraulic properties, and constructing numerical simulation models (Zapecza, 1985; Weiss, 1992; Thomas, *et al*, 1996; Domenico and Schwartz, 1998). With the rapid expansion of aquaculture and industry and deterioration in surface water resource, the demand of more accurate estimation of groundwater resource is never being so urgent in the Pingtung plain, especially along the coast region. A three-aquifer-units with two confining layers (The Central Geological Survey, 1997; Huang, *et al*, 1998; Lee, *et al*, 1998; Ting 1997 and 1998) has been the hydrogeologic framework for the shallow aquifer system (< 250 m) of the Pingtung plain since the beginning of the construction of the Groundwater Monitoring Network Plain (GMNP) in Taiwan. The GMNP in Taiwan was originated in 1992 and has been profoundly useful since 1995 in the study area. This project establishes not only groundwater monitoring wells that provide basic long-term hydrologic and hydrogeologic information but also conducts hydrology and hydrogeology researches that characterize hydrology regime and identify the hydrogeologic system.

Huang *et al* (1998) and the Central Geological Survey (CGS) (1997), after numerous tedious working hours, constructed the first and most detailed shallow hydrogeologic framework, four aquifers and three aquitards, of the Pingtung plain. Aquifers were named as aquifer 1, 2, 3 and 3-1 and aquitards were noted as T1, 2, and 3. Nine cross-sections were completed to show the detail stratigraphic distributions mainly based on the observations of grain size from sediment cores drilled during the first two years of the monitoring network. Aquifers are mainly composed of gravel and coarse sand while aquitards consist of primarily clay and silt. Lee (1998) and Ting (1997 and 1999) also presented a similar framework basically based on the Huang's framework. Liu *et al* (1998) studied groundwater system of the Pingtung plain using tritium as a tracer and showed an interesting distribution pattern in the southeastern area of the study area at depth between 100 and 150 below the mean sea level. This tracer study provided the first opportunity to reexamine the regional hydrogeologic framework. A small strip gap without the occurrence of tritium in the southwestern corner and no tritium was found in the west section of the plain at this particular depth.

Collecting 1995,1996 and 1998 data mainly from the Water Conservancy Agency (WCA) and Central Geological Survey (CGS), we constructed an alternative hydrogeologic framework, the upper and lower aquifer and one confining layer, of the shallow (<250 m) Pingtung plain (Kuo and Wang, 1999 and 2000a and b) primarily based on the integrative interpretation of borehole well logs, geophysical data, pumping tests results and groundwater levels. This delineation of this alternative framework receives strong support from the groundwater level fluctuations. Seawater intrusion also provides a window for us to reexamine the delineation via using the vertical distribution of the total dissolved solid distribution in the coastal area of the Pingtung plain.

STUDY AREA

PHYSICAL SETTING

The study area is located in the southwest of Taiwan with relatively well defined geomorphic boundaries, a high angle Chao-Chou thrust fault to the east, Miocene to Oligocene sandstone and shale to the north, Pleistocene conglomerate and sandstone foothill to the west, and the Taiwan Strait to the south (Fig. 1). The plain, an elongate in shape with area 1210 km^2, is roughly 55- km in length and 20 km in width. With the highest point of the plain, 80 m above the mean sea level, located in the northeast uppermost corner, the plain dips to southwest direction with a very gentle slope. The groundwater, thus, flows from northeast to southwest direction in general. As an alluvial deposit plain adjacent to the mountain range with three major rivers in it, the study area can be easily divided into three components, a proximal fan, mid-fan and distal fan mainly based on grain size (Fig. 1). The proximal fan is composed of more than 60% of gravel and 20% of sand while the mid-fan consists of 40% of gravel and 40% of sand (Taiwan Sugar Co., 1998). In general, the grain size decreases from east to west and from north to south. Clay and silt primarily were found in the distal fan with the most limited extend to the mid-fan area in the central portion of the plain.

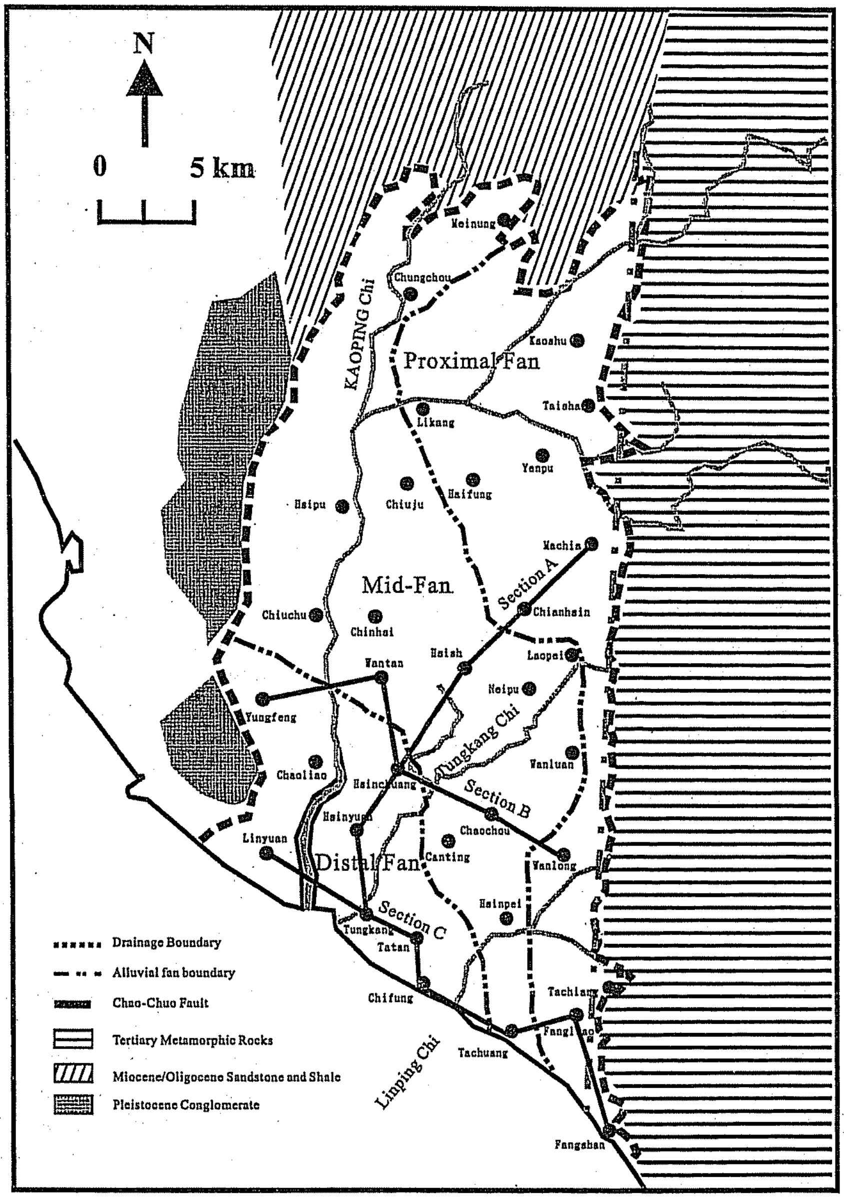


Figure 1. The location map of the Pingtung plain. A high angle Chao-Chou fault to the east, Miocene to Oligocene sandstone and shale to the north, Pleistocene conglomerate and sandstone foothill to the west, and Taiwan Strait to the south. Three cross-sections of the study area were shown

HYDROLOGIC BACKGROUND

The study area receives about 1200 mm of precipitation annually in the plain area while the mountain region can get as much as 3000 mm or more annually (Water Resources Bureau, 1998). However about 90% of the total annual precipitation is concentrated to fall during the period of May to October by typhoons and monsoon. This distinctive spatial distribution posts a vital challenge for the hydrology study and water resource management of the region.

Three major river systems, Kaoping, Tungkang, and Linping, flow through the entire study area (Fig. 1). The surface runoff bears the similar characteristic with the precipitation, a high value in the wet season between May and October.

The long-term groundwater level in the proximal fan area reflects very minor fluctuations before 1993. The level started to decrease during 1993 and 1994, and then recovered slowly. However, the level has never recovered to the level before 1993 since (Water Resources Bureau, 1998). In both the mid-fan and distal fan areas, the groundwater level has been decreased since 1980 due to the booming of the aquiculture industry and excess of domestic water usage. This decrease triggered seawater intrusion and land subsidence in the distal area, especially along the coastal area.

RESULTS AND DISCUSSION

Most of the alternative regional hydrogeologic framework has been built based on the correlations of sediment grain size from well samples with the assistance of the response of electrics and gamma ray logs. Groundwater level fluctuations from different depth screens were used to check the delineation at that particular site when available. Pumping test results, transmissivity, and isotopic data, carbon 14 yBP, were utilized to check the continuity of the conceptual model within the alternative hydrogeologic framework. The construction of this alternative framework is under the scope of the basin scale of the Pingtung plain. Groundwater data were collected from the Water Conservancy Agency, Taiwan, information of pumping tests and well loggings were gathered from the reports of the Central Geological Survey, Taiwan, and isotopic data were integrated from Liu and Wang (1998), respectively.

The relationships of subsurface stratigraphic and hydrogeologic units within the study area were shown in Table 1. The aquifer units correspond mainly to the braided river deposit environment while the confining layer reflects mostly the offshore to estuary depositional environment. This relationship can be served as the basis for estimation of hydraulic conductivity in spatial distribution once hydraulic conductivity is established for the unit. Detailed estimation of hydraulic conductivity of the study area is currently ongoing under the corporation with the Central Geological Survey and Institute of Earth Sciences, Academia Sinica.

Gravel and coarse sand account for more than 80% of the composition in the proximal fan. This phenomenon holds true not only on the surface but also down to the depth of 250m below the mean sea level. Therefore the entire proximal fan can be considered as one aquifer down to the depth of 250 m below the mean sea level. The most effort was given in the mid-fan and distal fan area for the construction of the alternative hydrogeologic framework. The detailed occurrence and configuration of three hydrogeologic units were discussed in the followings with the company of three cross-sections (Figs. 2, 3, and 4).

Table 1. Geological and hydrogeologic units i the Pingtung plain.

System	Series	Geologic Unit		Lithology	Hydrogeologic Unit
Quaternary	Holocene	Alluvial Deposits	BR	Gravel/ Coarse sand	Upper aquifer
			P/SO	Silt/Clay	Confining layer
			BR	Gravel/Sand	Lower aquifer

BR= Braided River Deposit Environment
P= Estuary Deposit Environment
SO= Shore Face to Offshore Deposit Environment

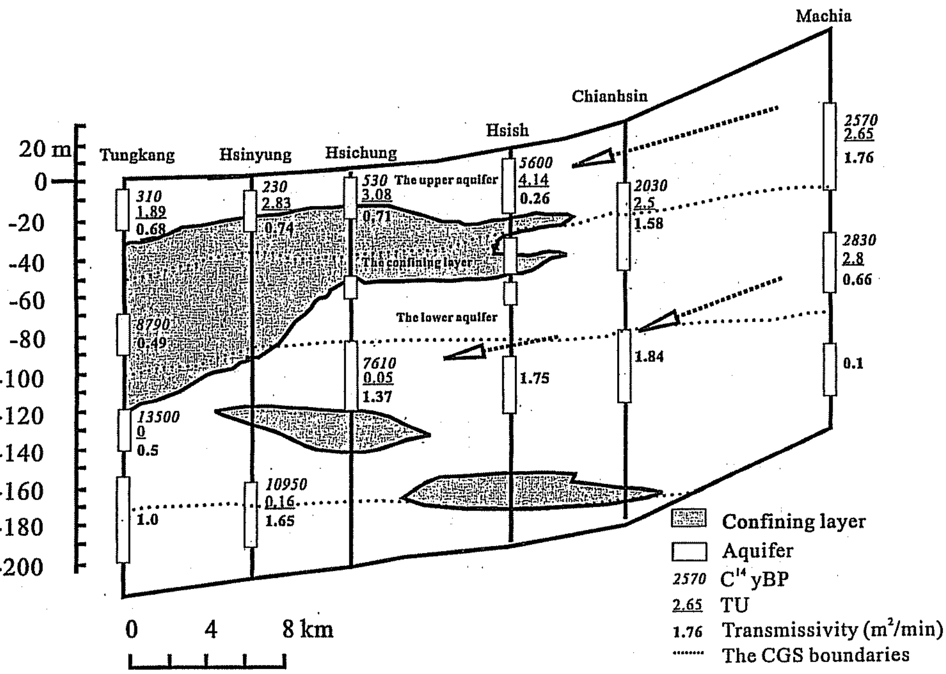


Figure 2. The hydrogeologic framework of cross-section A. The second and third screens of well Hsichung are located in the same aquifer, the lower aquifer. Data were taken from Taiwan Sugar Co., 1998, Liu (1998 and 1999), and the Central Geological Survey, 1997.

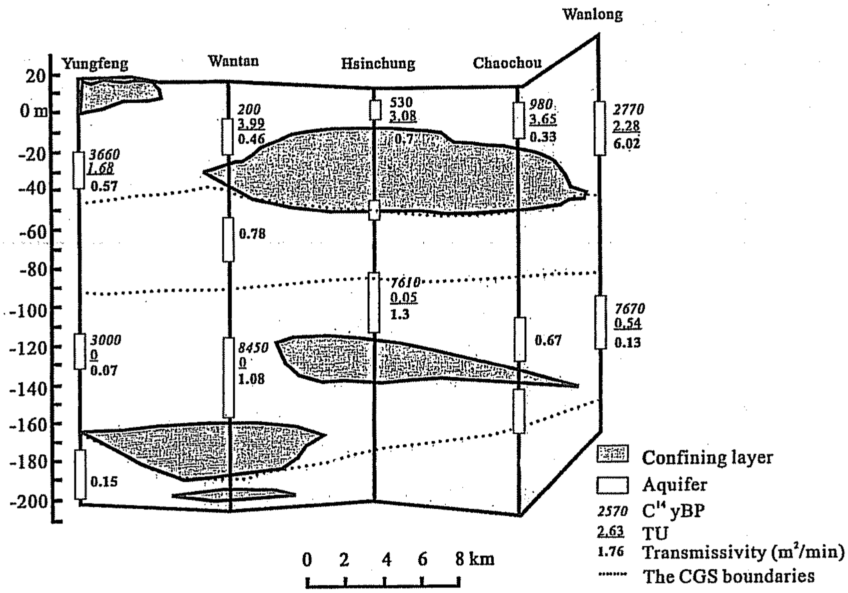


Figure 3. The hydrogeologic framework of cross-section B. No continuous confining layer was found below 70m. Data were taken from Taiwan Sugar Co., 1998, Liu (1998 and 1999), and the Central Geological Survey, 1997.

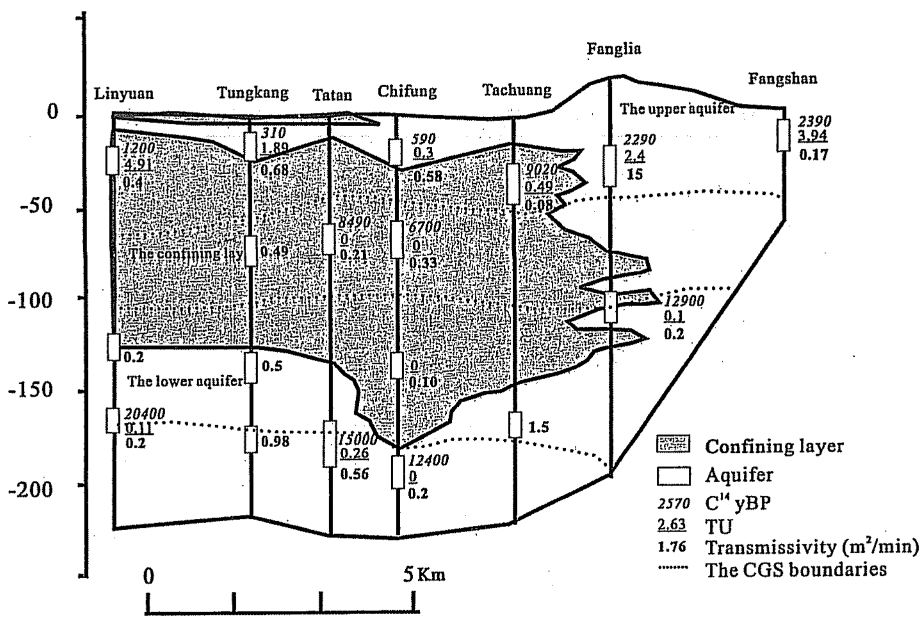


Figure 4. The hydrogeologic framework of cross-section C. No continuous confining layer was found to the east beyond well Fanglia. Data were taken from Taiwan Sugar Co., 1998, Liu (1998 and 1999), and the Central Geological Survey, 1997.

UPPER AQUIFER

Figure 2 illustrates the north-south direction of the regional hydrogeologic framework while Figures 3 and 4 shows the east-west direction of the regional hydrogeologic frameworks of the south part of the Pingtung plain. The top altitude of the upper aquifer from the mean sea level near the coastal area rises to 44 m above the mean sea level around well Wanlong (Figs. 1 and 3). In general, the thickness of the upper aquifer is less than 50 m with the thinnest thickness, about 20 m, around wells Hsinchuang, Linyan, and Tantan areas. The bottom of the unit is from about 15 m below the mean sea level at well Liyuan to around 50 m below the mean sea level at well Hsinchung. This aquifer is mainly composed of coarse sand in the distal and mid fan areas and coarse sand and gravel in the proximal fan area. However, silt and clay are locally interbeded with sand and gravel, especially in the distal fan area.

Most of the upper aquifer is under water table condition except the area near the coast such as wells Tachuang, Tungkang and Linyuang (Fig. 4). The transmissivity values of this unit range from 0.26 m^2/min at well Hsish to 0.74 m^2/min at well Hsinyung (Taiwan Sugar Co., 1998). Due to the fair average transmissivity and close to the surface, this unit is the most utilized aquifer in the region with a fair average of hydraulic conductivity, 1.0 x 10^{-4} m/sec (Taiwan Sugar Co., 1998; Wu, 1998). The age of ^{14}C are between 200 yBP at well Wantan and 530 yBP at well Hsinchung while the TU values are ranging from 0.3 at well Chifung to 4.14 at well Hsish. Both TU and ^{14}C values showed a trend of decreasing from north to south direction. This indicates that this aquifer were intensely mixed with surface water due to pumping and surface water infiltration.

CONFINING LAYER

The confining layer is areally limited by well Hsish to the north, well Hsinpei to the east and well Wantan to the northwest (Figs.1, 2 and 3). The only area the confining layer was found west of the Kaoping River is around well Linyuan area. However, the detailed distribution of this unit for the west part of the Kaoping River requires more updated data. The altitude of the top of this layer ranges from 20 m below the mean sea level at well Hsinchuang to 50 m below at well Tachuang and Chifung. On the other hand, the altitude of the bottom of this layer is from 160 m below the mean sea level near the coastal area to around 40 m around the mid-fan area. In general, the thickness of the confining layer decreases toward the inland direction and diminishes around well Hsish area (Fig. 2).

This unit is mainly composed of clay and silt with poor conductivity, 9.9 x 10^{-7} m/sec (Wu, 1998). The transmissivity of this unit ranges from 0.1 m^2/min at well Chifung to 0.49 m^2/min at well Tungkang. The transmissivity values are significantly less than that of the upper aquifer. No significant confining layer was found around well Wanlong to the east and Yungfeng to the west (Fig. 3) based on the continuity of the transmissivity and well logs. This indicates that this confining layer is gradually diminishing as it reaches the cross-section C. This delineation of the alternative hydrogeologic framework receives strong supports from the groundwater level fluctuations at well Wanlong to proof no hydrogeologic boundaries in the area. The identical groundwater level fluctuations at well Wanlong from Nov. 1, 1995 to Nov. 26, 1997 in magnitude and pattern from screens 1 and 2 clearly demonstrates that both screens are located under the same aquifer condition (Fig. 5). Using groundwater fluctuations to support the delineation of hydrogeologic framework has been used else where such as Chia *et al* (1996) in the Choshi River alluvial fan. This confining layer also played as an obstacle to prevent groundwater from flowing to the west part of the plain at depth 100-150 m below the mean sea level and possibly caused tritium to disappear in the west section of the plain at this particular depth. However, the cause of the small gap of the tritium distribution on the lower right side of the study area from Liu (1998) remains to be studied further.

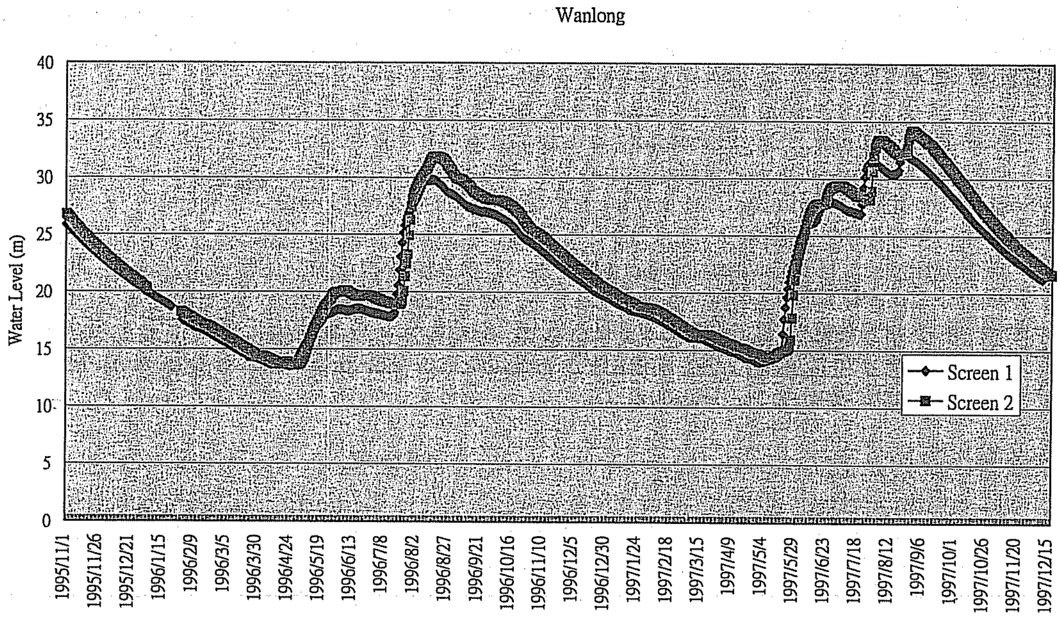


Figure 5. Groundwater level fluctuations of screens 1 and 2 from November 1, 1995 to November 26, 1997 at well Wanlong. The identical curve indicates both screens are under the same aquifer condition.

LOWER AQUIFER

The altitude of the top of the lower aquifer is the altitude of the bottom of the confining layer. Several major local perched confining layers were found below 130m (Figs. 2, 3 and 4) but no proof of continuity of those layers. The upper aquifer is connected to the lower aquifer on the west of the Kaoping River beyond Chaoliao toward inland. This connection may have some influence on local groundwater flow pattern if there is lateral input cross the west boundary. The groundwater level fluctuations at well Hsinchuang from separated screens at different depth support this delineation (Fig. 6). Both groundwater levels are almost identical in pattern and magnitude indicating that screens 2 and 3 are under the same aquifer condition.

The values of transmissivity in the distal fan and mid fan area in the upper aquifer are generally less than 1 m^2/min (Fig. 2) while those in the lower aquifer are higher than 1 m^2/min

(Taiwan Sugar Co., 1998) in the cross-section A. This distinctive difference indicates the presence of two different hydraulic systems, e.g. two different aquifers. Isotopic data also demonstrates the same pattern of two different systems in the upper and lower aquifers (Fig. 2). It clearly exhibits that groundwater flow takes separate path around well Hsish area and develops into two different groundwater systems. However, wells adjacent to the coast show less transmissivity values such as wells Tunkang, Chifung, and Tatan. Those well areas have been reported as the areas where seawater intruded. The lower value of transmissivity may be resulted from the alteration of hydraulic conductivity and transmissivity by the intrusion. The effect of seawater intrusion on hydraulic conductivity and transmissivity has been studied constantly (Mehert and Jennings, 1985; Goldenberg, 1985; Bond and Bredhoeft, 1987; Bear *et al*, 1999). This is due to the importance of its impact on both freshwater discharge and seawater intrusion to coastal aquifers. Mehnert and Jannings (1985) pointed out that ionic strength of percolating water could have greatly altered a soil's hydraulic conductivity. This alteration can increase brackish water to penetrate a coastal aquifer and contribute to the seawater intrusion front due to dispersion (Reilly and Goodman, 1985; Mehnert and Jennings, 1985). This is largely due to swelling of clay particles by water ionic strength (Goldenberg, 1985; Mehnert and Jennings, 1985).

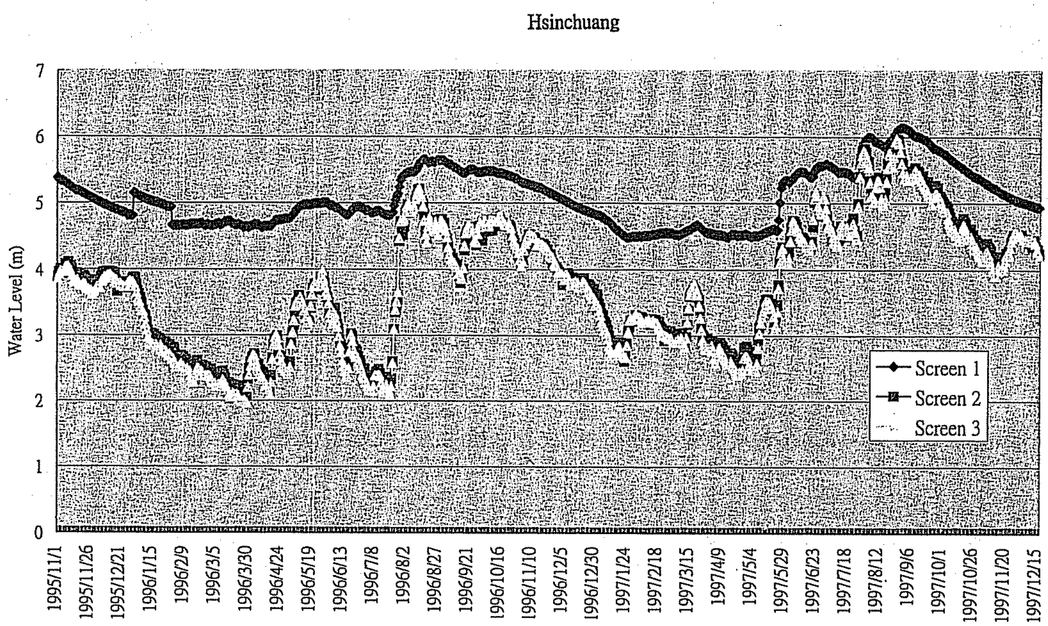


Figure 6. Groundwater level fluctuations of screens 1, 2 and 3 from November 1, 1995 to November 26, 1997 at well Hsinchung. The identical curve of screen 2 and 3 indicates both screen are under the same aquifer condition.

TOTAL DISOLVED SOLIDS DISTRIBUTION

Using the total dissolved solids (TDS) to identify seawater intrusion in coastal aquifers is an effective method (Bear *et al*, 1999). The TDS distribution in the study area was studied in careful comparison with well resistance and spontaneous potential curves studies (Chiang and Wang, 1998). This is because salinity can decrease the electric resistance in a well and cause the resistance and spontaneous potential curves to deflect to the left. The records of resistance and spontaneous potential curves were not as significantly sensitive in the study area, a sharp negative deflection, on the seawater intrusion. The frequent presence of interbeded silt and clay may have decreased the sensitivity of electric detections in the region. However, higher values were observed near the coast, such as Tangkung, and lower values were recorded away from the coast area, such as Hsinchung.

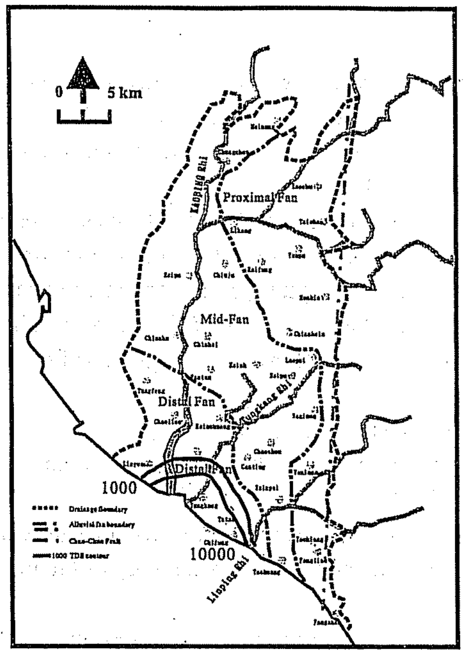
Chiang and Wang (1998 and 1999) studied the seawater intrusion in the Pingtung plain via measuring the total dissolved solids. In general, fresh water has TDS value less than 1000 mg/l while saline water higher than 10000 mg/l (Freeze and Cherry, 1979). We propose here a definition of the mixing zone as an area contains the TDS value between 1000 and 10000 mg/l. The average width of this mixing zone in the CGS aquifers 1 and 3 are about 2 to 2.5 km respectively while the average width of the mixing zone of CGS aquifer 2 is about double, 5 km (Fig. 7). In addition, the average width of the mixing zone in the CGS aquifer 1 is smaller than that of the CGS aquifer 3, particularly near the Linpeing River area. This is because this aquifer is the most utilized aquifer in the study area and results in the quicker recharge rate locally. Quicker infiltration of surface water into this aquifer may also result in this smaller width of TDS. This almost double width of the mixing zone in the CGS aquifer 2 indicates the presence of a slower fresh water recharge rate at the particular depth. The slower recharge rate may be resulted from the lower in-situ hydraulic conductivity present since the CGS aquifers 2 and 3 are under the same nature groundwater gradient from the basin-scale perspective. This lower hydraulic conductivity zone matches the confining layer in the alternative regional hydrogeologic framework. We, thus, mark this lower hydraulic conductivity zone, the 5 km mixing zone, as a confining layer, which matches quite well with the alternative hydrogeologic framework.

CONCLUSION

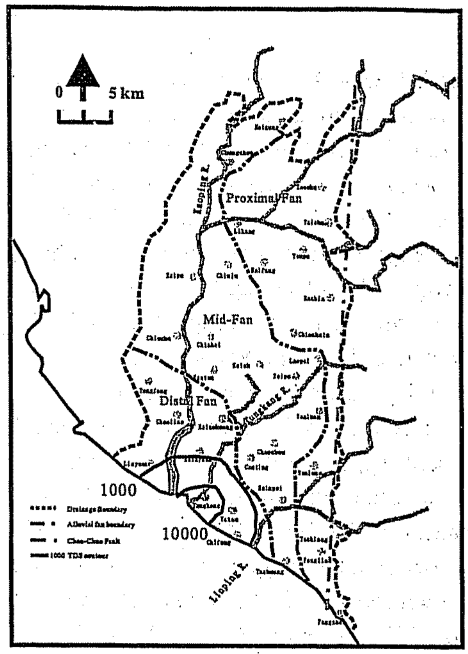
The basin scale of regional hydrogeologic framework, two-aquifers with one confining layer, was constructed based mainly not only on grain size, but also groundwater level fluctuations and pumping test results. This alternative framework delineation properly reflects groundwater level fluctuations from different screens and also shows the continuity of transmissivity and isotopic data, especially along the north-south profile. The vertical distribution of the total dissolved solids near the coastal area provides another support for this basin scale hydrogeologic framework delineation of the Pingtung plain.

ACKNOWLEDGMENTS

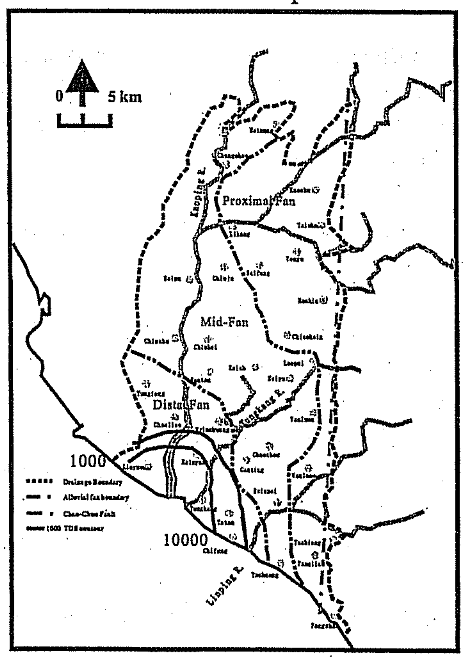
The authors would like to thank the Hydrogeology Division of the Central Geological Survey for their help and discussions. We would also like to thank the Water Conservancy Agency, Ministry of Economic Affairs for their help on data retrieving. This study was supported by the National Science Council, R. O. C. under the grant NSC 88AIA0100283.



Aquifer 1



Aquifer 2



Aquifer 3

Figure 7. The vertical distribution of total dissolved solids in mg/l. The width of the mixing zone is about 2 km in aquifers 1 and 3 while it is about 5 km in aquifer 2. (modified from Chiang and Wang, 1998)

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