Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99 Symposium HS5, Birmingham, July 1999). IAHS Publ. no. 259, 1999.

Deterioration of groundwater quality in the coastal Pingtung Plain, southern Taiwan

CHUNG-HO WANG
Institute of Earth Sciences, Academia Sinica, PO Box 1-55, Nankang, Taipei, Taiwan 11529
e-mail: chwang@earth.sinica.edu.tu

CHUNG-JUNG CHIANG
Central Geological Survey, PO Box 968, Taipei, Taiwan 23557

TSUNG-REN PENG
Department of Soil and Environmental Sciences, National Chung Hsing University, Taichung, Taiwan 40227

WEN-CHEH LIU
Department of Horticulture, Taiwan Sugar Research Institute, Tainan, Taiwan 70123

Abstract Population growth, urban expansion and economic development have persistently raised the demand for water supply and consequently, greatly increased the exploitation of groundwaters in the Pingtung Plain of southern Taiwan over past decades. Over-pumping of groundwaters, due to booming freshwater aquaculture and agricultural activity, has caused the groundwater level to fall and land to subside below sea level in some coastal areas. Isotopic and chemical groundwater analysis has verified the deterioration in coastal groundwater quality, due to active seawater intrusion through the offshore outcrops of both unconfined and confined aquifers, since 1980. The greatest extent of seawater encroachment has been estimated to be as far as 8.5 km inland with an affected area of about 104 km^2 for the deep confined aquifer in 1996. Remedial measures need to be immediately enforced to effectively restrain sea water encroachment and to alleviate groundwater salinization.

INTRODUCTION

The Pingtung Plain covers an area of 1210 km^2 and is located in the southwestern part of Taiwan. It consists of unconsolidated sediments of the late Pliestocene and Holocene period and is bounded by low hills of Quaternary sediments to the north and west, by the Central Mountain Range of Tertiary rocks to the east, and by the Taiwan Strait on the south (Fig. 1). Since 1992, the initiation of a groundwater monitoring programme in Taiwan has established an important hydrogeological database within the study area (CGS, 1997). The subsurface hydrogeology can be illustrated by a vertical profile along the line from the drill site M (Machia, with an altitude of 85 m) to the offshore Kaoping canyon, 200 m below sea level (A) (Fig. 2). Generally, there are three aquitards (T1, T2, T3) and three to four aquifers (F1, F2, F3.1, F3.2) in the central area and southern coastal parts of Pingtung Plain. In the eastern region, a gravel bed extends to a depth of below 150 m making up an integrated and thick aquifer.

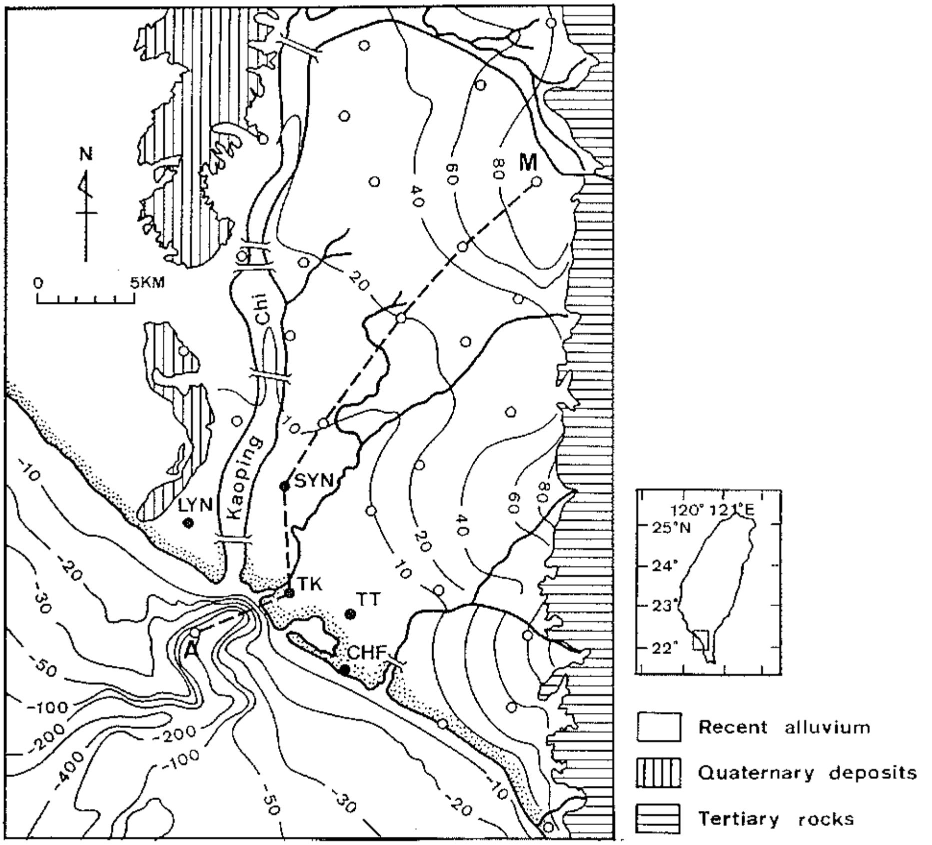

Fig. 1 Location of the Pingtung Plain. (The contour lines illustrate the general flow direction from northeast toward the southwest for groundwaters. Solid dots along the coastal region are wells of saline groundwaters.)

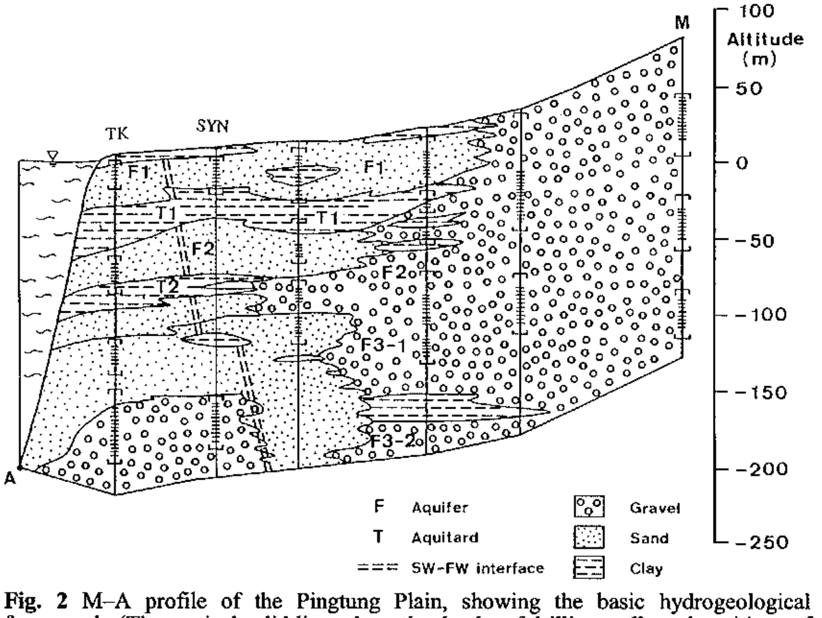

Fig. 2 M–A profile of the Pingtung Plain, showing the basic hydrogeological framework. (The vertical solid lines show the depths of drilling wells and positions of screens where groundwaters were sampled.)

In this paper, we present stable isotope and chemical evidence for the deterioration of coastal groundwater quality during the past two decades resulting from over-pumping associated with local anthropogenic activities.

DATA

More than 200 water samples were collected in the Pingtung Plain between August 1995 and July 1996 for stable isotope and chemical analyses. The drilling sites for the Groundwater Monitoring Program are illustrated as open circles in Fig. 1. Groundwaters from various aquifers and different levels were sampled by both multiple and independent methods. All isotopic data are tabulated in Wang *et al.* (1996b) and chemical compositions are taken from WCB (1995, 1996).

RESULTS AND DISCUSSION

Figure 3 illustrates the hydrogen and oxygen isotopic compositions of the Pingtung Plain groundwaters. Most groundwaters distribute along the local meteoric water line (MWL) and cluster in a relatively confined zone as might be expected. However, samples from five coastal wells (location as solid dots in Fig. 1) show anomalous values and lie along the mixing line between compositions of seawater and mean groundwater values, suggesting that these isotope-enriched groundwaters have been incorporated with various amounts of seawater.

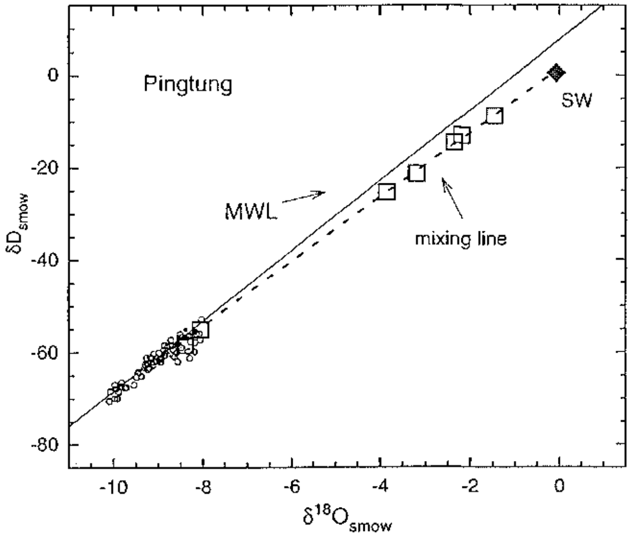

Fig. 3 Hydrogen versus oxygen isotopic compositions of groundwaters in the Pingtung Plain. (MWL is the local meteoric water line. SW represents isotopic compositions of seawater off the Pingtung Plain. Open circles stand for normal groundwaters. Open squares are those from five coastal wells; solid dots in Fig. 1.)

Figure 4 is a Total Dissolved Solid (TDS) contour map of groundwaters sampled during 1995/1996 for the deep confined aquifer F3.1 (location as open circles in Fig. 4). Most groundwaters exhibit typical freshwater values varying between 168 and 498 mg l^{-1}, except for those wells in the vicinity of the mouth of Kaoping Chi where they show values above 1000 and up to 29 000 mg l^{-1}. Other chemical analyses confirm that the deterioration of groundwater quality is due to the addition of seawater (WCB, 1996). During an early investigation in 1960 however, groundwaters in this same aquifer (sampling sites as cross symbols in Fig. 4) displayed normal TDS values ranging from 180 to 984 mg l^{-1} throughout the whole Pingtung Plain (GDB, 1961). This observation is also true for other aquifers (e.g. F-1, F-2 and F3.2), indicating that no pollution seawater signals existed in aquifers along the coastal area in 1960. The contour pattern in Fig. 4 not only shows the affected areas due to the intrusion of sea water but also reveals that the invading area has been initiating from outcrops offshore of the mouth of Kaoping Chi. Figure 2 shows that aquifers have outcropped along the Kaoping Canyon, offshore of the coastal Pingtung Plain, thus enabling a potential passage for sea water encroachment. Once the hydrostatic pressure balance was broken

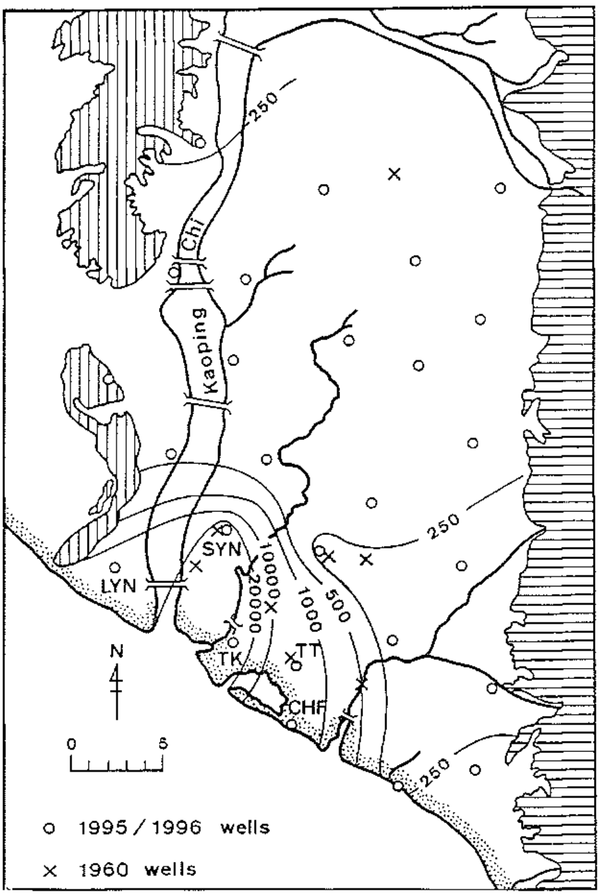

Fig. 4 Total dissolved solids contour map for aquifer F-3.1 in the Pingtung Plain. (Open circles are sampling sites in 1995/1996, whereas cross symbols denote those conducted in 1960.)

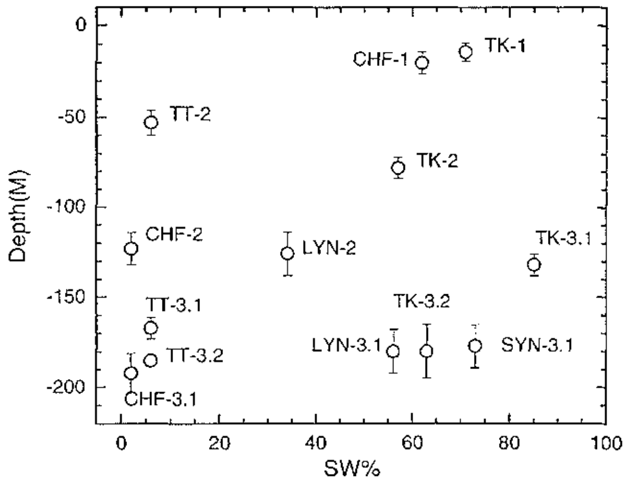

Fig. 5 Depth *vs* seawater content of wells from the coastal Pingtung Plain. (See Fig. 1 for well location. The error bar indicates the length of screen.)

due to groundwater over-pumping, sea water would naturally move inland through these outcropping aquifers.

Figure 5 presents a diagram of depth versus seawater content for the coastal groundwaters. The seawater contents were estimated by a linear mixing model using chloride ion and oxygen isotopes as the main parameters (Wang *et al.*, 1996a). This plot shows the coastal groundwaters have been contaminated with seawater from the top unconfined aquifer (F1) down to the deep confined aquifers (F3.1, F3.2). Tungkung well (TK) is the closest to the offshore outcrops and consequently suffers the most from seawater encroachment for all its aquifers (e.g. TK-1, TK-2, TK-3.1, TK-3.2).

The upper plot of Fig. 6 shows the numbers of wells and groundwater drafting amounts for the past 30 years in the Pingtung Plain. Both trends show a drastic rise around 1980 due to the booming of local aquaculture and expansion of agriculture activities, and the groundwater usage has begun to exceed the estimated natural annual recharge amount of about 10×10^8 m^3 for the first time. The middle and bottom diagrams show the rapid and coincidentally dropping of deep confined groundwater levels (F3.1) and subsidence of the land surface around 1980 due to over-pumping of groundwaters. The land surface below zero (sea level) altitude has also expanded inland since 1980 and now covers an area of about 105 km^2 along the coastal region.

Thus, a scenario can be reasoned from the aforementioned evidence: the demand for groundwater has increased drastically since 1980 owing to the expansion of both local aquaculture and agriculture activity, and caused an over-exploitation of groundwater resources, causing groundwater levels to fall as well as land subsidence. The hydrostatic balance between the groundwater and seawater interface has been broken, inducing seawater encroachment along the coastal Pingtung Plain, and consequently, heavily deteriorating the quality of coastal groundwaters. Aided by water chemistry, stable isotopes and well logging data, we have quantitatively estimated the extent of the saline groundwaters and placed the interface between the saline groundwaters and freshwater along the profiles, as illustrated by the dashed lines

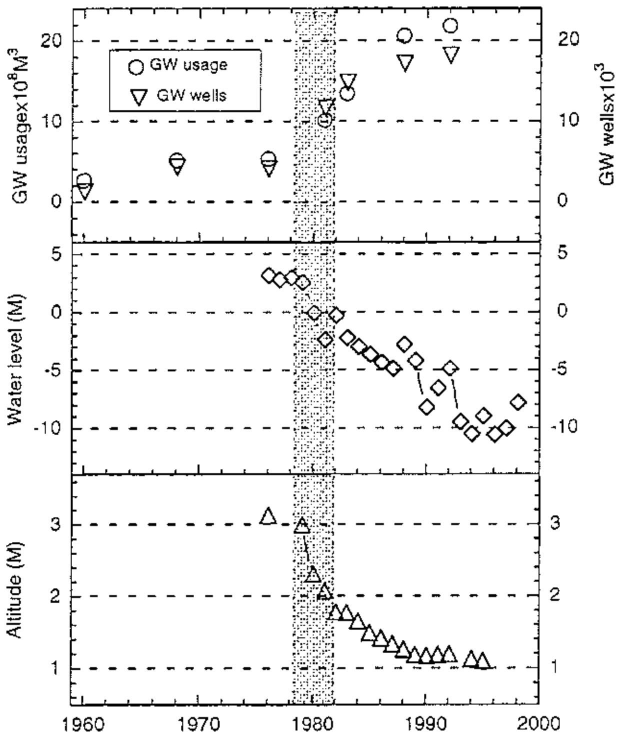

Fig. 6 Groundwater wells and drafting amounts (upper), water level (middle), land subsidence (lower) in the Pingtung Plain from 1960 to 1997. (The shadow line illustrates the rapid transition period of groundwater quality deterioration.)

in Fig. 2. In Table 1, the affected coastal areas, intruding depths and average intruding rates (1980–1996) due to sea water encroachment are listed by aquifers. This table shows a total affected area of 359 km^2 and an average invading rate of about 500 m year^{-1} by seawater encroachment. Up to 1996, the furthest intrusion was about 8.5 km inland. These figures strikingly illustrate the seriousness of this groundwater quality degradation along the coastal region. At present, seawater encroachment is still in progress. Remedial measures are needed immediately, with strict enforcement to effectively restrain the sea water encroachment and to alleviate the groundwater salinization. Further modelling work will be pursued in the next phase of work.

Table 1 Saline groundwaters caused by sea-water intrusion in the coastal Pingtung Plain.

Aquifer	F-1	F-2	F-3.1	F-3.2
Affected area (km^2)	66	81	108	104
Intruding depth (km)	6.5	7.5	8.3	8.5
Average intruding rate (m year^{-1})	406	469	519	531

Acknowledgement This work was funded by National Science Council (NSC85-2111-M001-023) and Academia Sinica.

REFERENCES

CGS (Central Geological Survey) (1997) *Report on Hydrogeology of the Pingtung Plain* (in Chinese). Groundwater Monitoring Program in Taiwan (I), 1995–1996. Ministry of Economic Affairs, Taipei, Taiwan.

GDB (Groundwater Development Bureau) (1961) *Report on the Investigation of Groundwaters in the Pingtung Plain* (in Chinese). Department of Reconstruction, Taichung, Taiwan.

Wang, C. H., Peng, T. R. & Liu, T. K. (1996a) The salinization of groundwater in the northern Lan-Yang Plain, Taiwan: stable isotope evidence. *J. Geol. Soc. China* **39**, 627–636.

Wang, C. H., Chang, T. C., Lin, Y. L., Liu, W. C., Li, L. A., King, S. H., Chang, P. C. & Lan, F. S. (1996b) *Natural Recharge to the Groundwaters in the Pingtung Plain, Taiwan: Isotopic Evidence* (in Chinese). Institute of Earth Sciences, Academia Sinica, IESCR96-021, Taipei, Taiwan.

WCB (Water Conservancy Bureau) (1995) *Report on Groundwater Monitoring Program in Taiwan (I). Appendix 2: The Chemical Analyses of Groundwaters in the Pingtung Plain* (in Chinese). Taichung, Taiwan.

WCB (Water Conservancy Bureau) (1996) *Report on Groundwater Monitoring Program in Taiwan (I): The Chemical Analyses of Groundwaters in the Choushuichi Alluvial Fan and Pingtung Plain* (in Chinese). Taichung, Taiwan.