Estimation of groundwater recharge using the chloride mass-balance method, Pingtung Plain, Taiwan

Cheh-Shyh Ting · Tienfuan Kerh · Chiu-Jung Liao

Abstract Due to rapid economic growth in the Pingtung Plain of Taiwan, the use of groundwater resources has changed dramatically. Over-pumping of the groundwater reservoir, which lowers hydraulic heads in the aquifers, is not only affecting the coastal area negatively but has serious consequences for agriculture throughout the plain. In order to determine the safe yield of the aquifer underlying the plain, a reliable estimate of groundwater recharge is desirable. In the present study, for the first time, the chloride mass-balance method is adopted to estimate groundwater recharge in the plain. Four sites in the central part were chosen to facilitate the estimations using the ion-chromatograph and Thiessen polygon-weighting methods. Based on the measured and calculated results, in all sites, including the mountain and river boundaries, recharge to the groundwater is probably 15% of the annual rainfall, excluding recharge from additional irrigation water. This information can improve the accuracy of future groundwater-simulation and management models in the plain.

Résumé Du fait de la croissance économique rapide de la plaine de Pingtung à Taiwan, l'utilisation des ressources en eau souterraine s'est considérablement modifié. La surexploitation des aquifères, qui a abaissé le niveau des nappes, n'affecte pas seulement la région côtière, mais a de sérieuses répercutions sur l'agriculture dans toute la plaine. Afin de déterminer les ressources renouvelables de l'aquifère sous la plaine, une estimation précise de la recharge de la nappe est nécessaire. Dans cette étude, le taux de recharge de la nappe a d'abord été estimé au moyen d'un bilan de matière de chlorure. Quatre sites de la partie centrale ont été sélectionnés pour réaliser ces estimations, à l'aide d'un chromatographe ionique et de la méthode des polygones de Thiessen. A partir des résultats mesurés et calculés, à chaque site, et en prenant comme limites les montagnes et les rivières, la recharge de la nappe a été évaluée à environ 15 % des précipitations annuelles, sans tenir compte de la recharge par le retour d'irrigation. Ce résultat doit permettre de tester la précision de la simulation de nappe qui va être faite, ainsi que les modèles de gestion de la plaine.

Resumen Debido al rápido crecimiento económico de la zona de la Llanura de Pingtung, Taiwan, el uso de los recursos de agua subterránea ha cambiado radicalmente. La sobreexplotación, con el consiguiente descenso de los niveles piezométricos en los acuíferos, no sólo afecta las áreas costeras, sino que está teniendo consecuencias importantes para la agricultura de la zona. Para determinar la extracción sostenible en el acuífero, es deseable una buena estimación de la recarga. En este estudio se adopta por primera vez el método de balance de cloruros para estimar la recarga en el llano. Se seleccionaron cuatro puntos en la parte central para facilitar las estimaciones mediante los métodos de cromatógrafo iónico y de polígonos de Thiessen. A partir de los resultados medidos y calculados en toda la zona, e incluyendo los contornos de montañas y ríos, la recarga subterránea es de cerca del 15% de la precipitación anual, excluyendo la recarga que se produce por riego adicional. Este dato permitirá mejorar la precisión de los modelos de simulación de flujo y de gestión que se realizarán en el futuro.

Key words Taiwan · groundwater recharge · water budget · chloride mass-balance method

Introduction

Groundwater is a significant part of the total water resources in many areas, and it commonly plays a key

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role in economic development. For instance, the Pingtung Plain, located in the southwestern part of Taiwan, is an important agricultural area that is adversely affected by recent water-resources development. Due to rapid economic growth, the use of groundwater resources has increased dramatically, and groundwater overdraft has become a serious problem in the coastal plain of Pingtung (Ting 1993). The extraction of groundwater has three major negative consequences: (1) overall water-level decline; (2) salt-water intrusion in coastal areas; and (3) land subsidence in coastal areas. Seawater intrusion and land subsidence in coastal areas are mainly caused by the withdrawal of groundwater for aquaculture. Fresh-water and brackish-water fish ponds use large amounts of groundwater to regulate salinity, oxygen, and temperature.

Aquacultural farming has proved to be more profitable than other methods of crop cultivation, and the government did not restrict the expansion of aquacultural farms until recently, when land subsidence occurred in some of the coastal areas. Consequently, many agricultural farms have switched to raising eels, clams, and shrimps. An eel farm consumes about ten times the amount of fresh water than that used by paddy fields (Lin 1986).

The extraction of large amounts of groundwater for these purposes is resulting in cumulative land subsidence exceeding 2.88 m. The Linpien area in Pingtung County is underlain by one of the most compressive aquifers in the world. About 1 m of subsidence occurs for every 5 m of water-level decline (Wen 1986a,b). Only 20% of the wells in the coastal area were registered with government permits, and a survey by the Chiayi Agricultural Junior College identified 3871 illegal wells in Pingtung County (Lin 1986). In 1961, 1351 wells were registered and estimates were that annual recharge was sufficient for drilling another 388 wells (Hsu 1961a). Over-pumping of the groundwater reservoir, which lowers the hydraulic head in the aquifers, is not only affecting the coastal area negatively but has serious consequences for agriculture in the whole Pingtung Plain. What will be needed in the near future is an efficient management of the groundwater resources. In order to determine the safe yield of the aquifer underlying the Pingtung Plain, a reliable estimate of groundwater recharge is needed.

The Provincial Groundwater Development Bureau made a first estimate of recharge in the Pingtung Plain in 1961, by subtracting average annual runoff and evaporation from the total rainfall, resulting in an estimate of 903 million m^3 (Hsu 1961b). This amount is equivalent to 14% the total annual rainfall. The Pingtung Plain is intensively cultivated and recharge is consequently also the result of excess irrigation in addition to the natural recharge mechanisms, such as rainfall infiltration and percolation through river beds. More than three decades have passed, and the conditions in the plain have changed significantly. Therefore, it is appropriate to make a new estimate of groundwater recharge to improve the accuracy of groundwater management models in the plain.

Many methods can be used to estimate groundwater recharge for the first time, such as direct measurements, water-balance methods, Darcian approaches, and tracer techniques (Lerner et al. 1990). In the present study, a tracer technique, in particular, the chloride mass-balance method, is used to estimate groundwater recharge in the Pingtung Plain. The chloride ion is used in chemical recharge studies because of its conservative nature. The ion neither leaches from nor is absorbed by the sediment particles, and the ion does not participate in any chemical reaction. The ion is assumed to move through the unsaturated zone with the same velocity as water particles. As a result, abstraction of water in the root zone due to evapotranspiration of the plant is the only process that concentrates the ion in the soil moisture. The recharge estimation is based on the input of water and chloride at the surface and the soil-moisture and chloride contents in the soil profile. The chloride input consists of the wet deposition of chloride dissolved in rain and the dry deposition of aerosols. Details of recharge mechanisms and chloride profiles are contained in Allison (1988).

The objective of this study was to estimate groundwater recharge using the chloride mass-balance method in the plain. Four sites on a section that is parallel to the direction of the regional groundwater flow (Wu 1995) were used to evaluate groundwater recharge by the mixing-cell method.

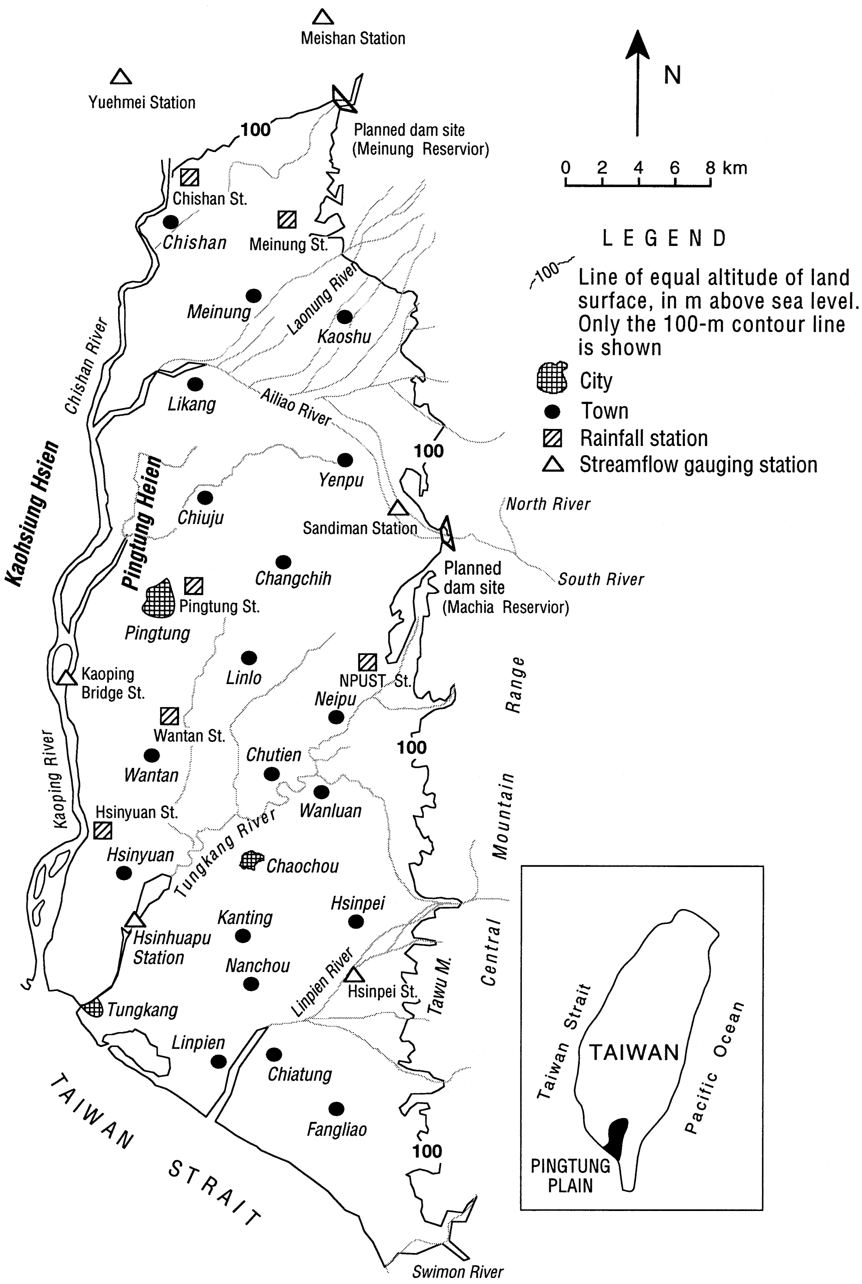
Physical Features of the Pingtung Plain

Taiwan, located in the subtropics, is an island of substantial rainfall, with an annual average of 2515 mm (Ting 1993). The average precipitation for the Pingtung Plain is even greater (3130 mm/yr; Ting 1993). Its distribution throughout the year is quite uneven, and most of the precipitation is brought by typhoons in the rainy season. In the Pingtung Plain, the wet season is largely confined to five months (May to September). The rainfall during this period is about 89% of the annual precipitation. Consequently, the annual rate of effective rainfall is very low (Hsu 1961b; Tsao 1972). Locations are shown in *Figure 1*.

Figure 2 shows the precipitation and evaporation as measured in 1988 and 1994 at the meteorological station at the National Pingtung University of Science and Technology (NPUST) in Neipu. The total rainfall was 2741 mm in 1988 and 3178 mm in 1994; annual evaporation was 1364 mm in 1988 and 990 mm in 1994 (Ting et al. 1998). The enormous amount of precipitation in August and September is not exceptional compared to other years and is characteristic for the rainfall distribution in Taiwan. Average annual temperature in Pingtung is 24° C; the highest monthly mean value is in July (28° C), and the lowest is in January (19° C).

As shown in *Figure 3*, the plain is bounded by low hills in the north, by foothills lying along the right bank

Fig. 1 Location of the Pingtung Plain, Taiwan



of the Kaoping River in the west, by the Central Mountain Range in the east, and by the Taiwan Strait in the south. The plain includes three alluvial fans, namely Ailiao, Tungkang, and Lingpien. The unconsolidated sediments underlying the plain are of Quaternary age and constitute the main aquifer for this groundwater region (Hsu 1961b).

The mountainous regions surrounding the Pingtung Plain are underlain by rocks of Tertiary age. Included are Eocene–Oligocene black slate intercalated with sandstone on the western flank of the Central Mountain Range (Suao Group); Miocene–Pliocene sandstone and shale in the northern region (Mucha Formation); and Pliocene sandy shale (Kutingkeng Formation) and shale and sandstone (Chiting Formation), both in the northwestern part of the plain (Hsu 1961a). All formations possess poor water-bearing properties, which results in high runoff rates. Only joints and cleavages are available for storage of water, and these are insufficient to regard any of these formations as a potential aquifer.

The unconsolidated sediments underlying the Pingtung Plain are of Quaternary age and form the main aquifer in the area. They consist of Lingkou conglomerate along the western edge of the hilly region north of the plain, older coarse alluvium at the mouth of the Ailiao and Chianapu Creeks, and recent alluvium that underlies most of the plain. The latter deposits consist of fan-like deposits and sediments from broad, braided river valleys. They include coarse gravel, gravel alternating with sand, and an accumulation of clay, silt, and black sand derived from slate (Hsu 1961a). Groundwat-

Fig. 2 Monthly rainfall and pan evaporation at NPUST, 1988 and 1994

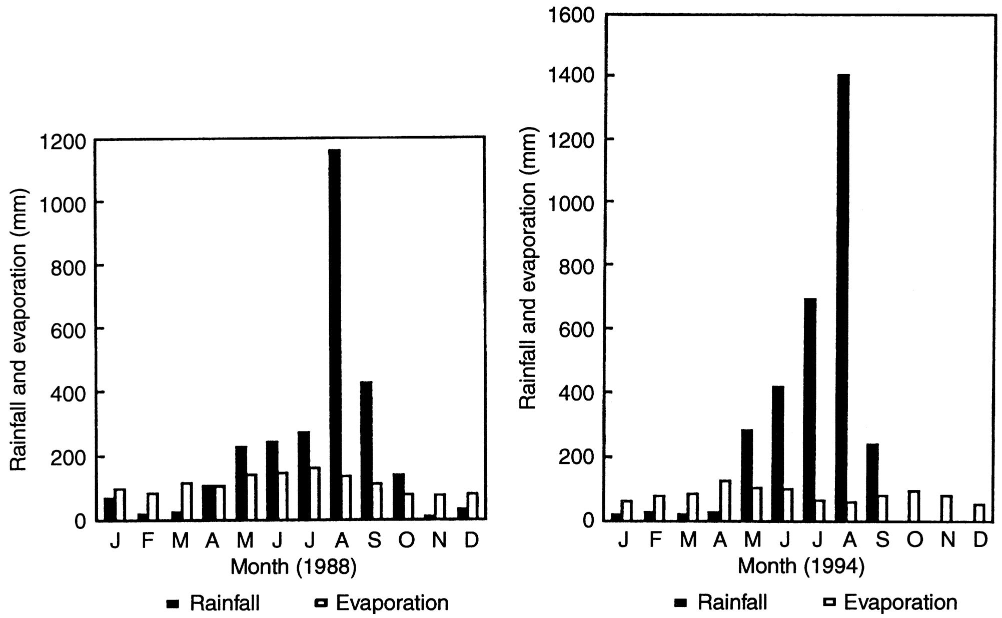
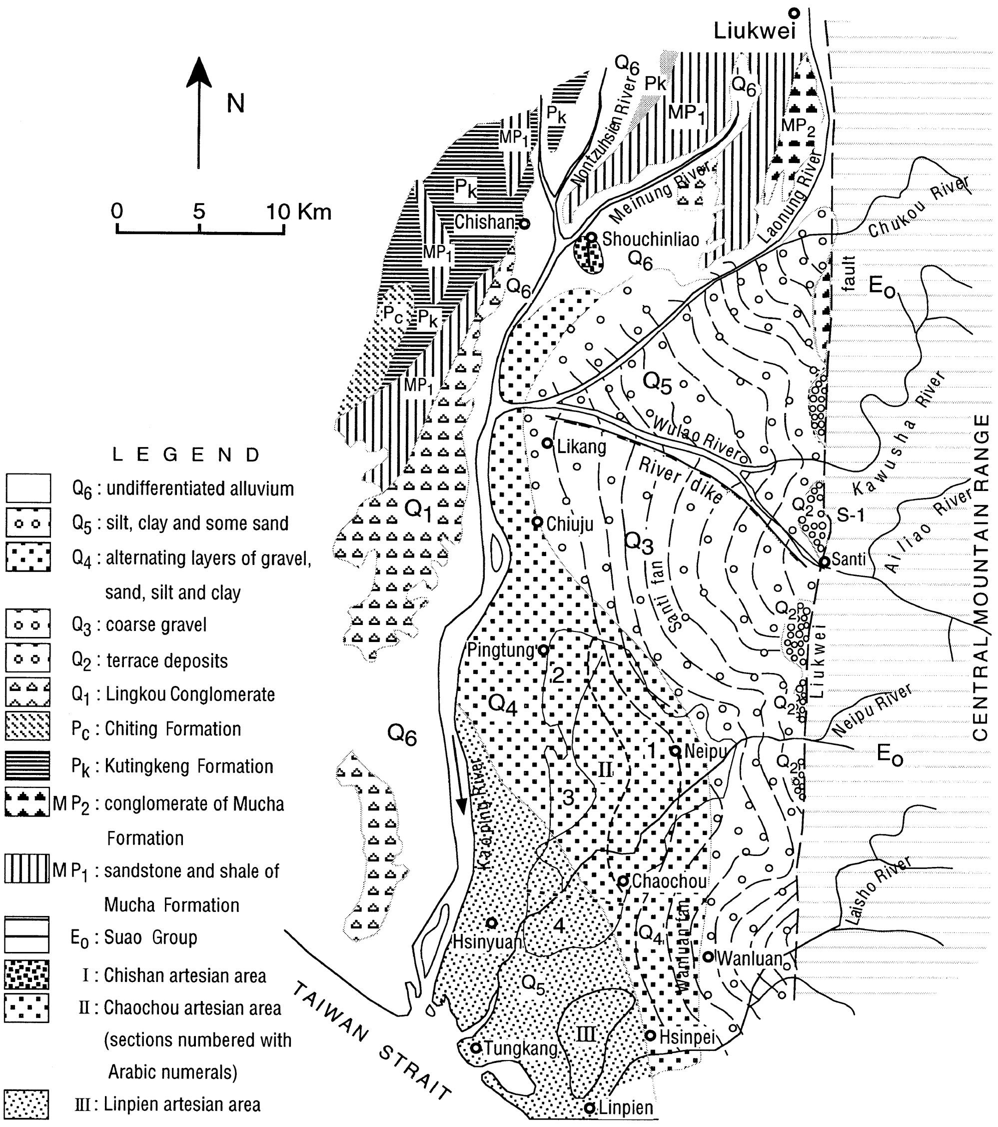


Fig. 3 Geology of the Pingtung Plain region. (After Hsu 1961a)



er is derived principally from direct precipitation onto the plain and partly from influent river seepage. Recharge occurs mainly by direct infiltration through unconsolidated deposits along the foothill belts to the north and east and from infiltration of rivers in the upper part of the plain. Groundwater moves generally westward to the Kaoping River, the Tungkang River, and southwestward to the sea (Ting 1993).

The Pingtung Plain is underlain mainly by alluvial soils developed in Quaternary-age deposits. The distributions of various soil types and soil textures are shown in *Figures 4* and *5*. These alluvial deposits consist of non-calcareous older soils (At 5) and calcareous younger soils (At 6). The soils are weakly developed to undeveloped, with moderate to large permeabilities. Along the eastern boundary of the project area, near the mountain range, Diluvium or Pleistocene red soils (Rp) occur that were formed in ancient alluvial deposits. The landform varies and includes lateritic terraces, diluvial uplands, and very old alluvial terraces. The latter are on the campus of the NPUST, where an oxysol has been developed. Strong laterization may occur in these soils, thereby decreasing the infiltration capacity substantially.

Yellow and colluvial soils originating from metamorphic rock (Ym and Cm, respectively) occur sporadically near the mountain range but are of minor importance. In the northernmost part of the project area, sandstone–shale alluvial and colluvial soils (Ax, Cs, Ys, Ds, and Yp) that are imperfectly drained have developed (Sheh and Wang 1991). An indication of the variability in texture is provided in *Figure 6* for the Kaoping River basin (WRPC 1985).

Models of the Chloride Mass-Balance Method

Groundwater recharge is defined as the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone (Freeze and Cherry 1979). Two principal types of recharge are recognized, i.e., direct (local or diffuse) and indirect (localized) recharge. Direct recharge is defined as water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration by direct vertical percolation of precipitation through the unsaturated zone. Indirect recharge results from percolation to the water table following runoff and localization in joints, such as by ponding in low-lying areas and lakes or through the beds of surface watercourses (Lerner et al. 1990).

The chloride mass-balance method developed by Eriksson and Khunakasem (1969) compares total chloride deposition at the surface with chloride concentrations

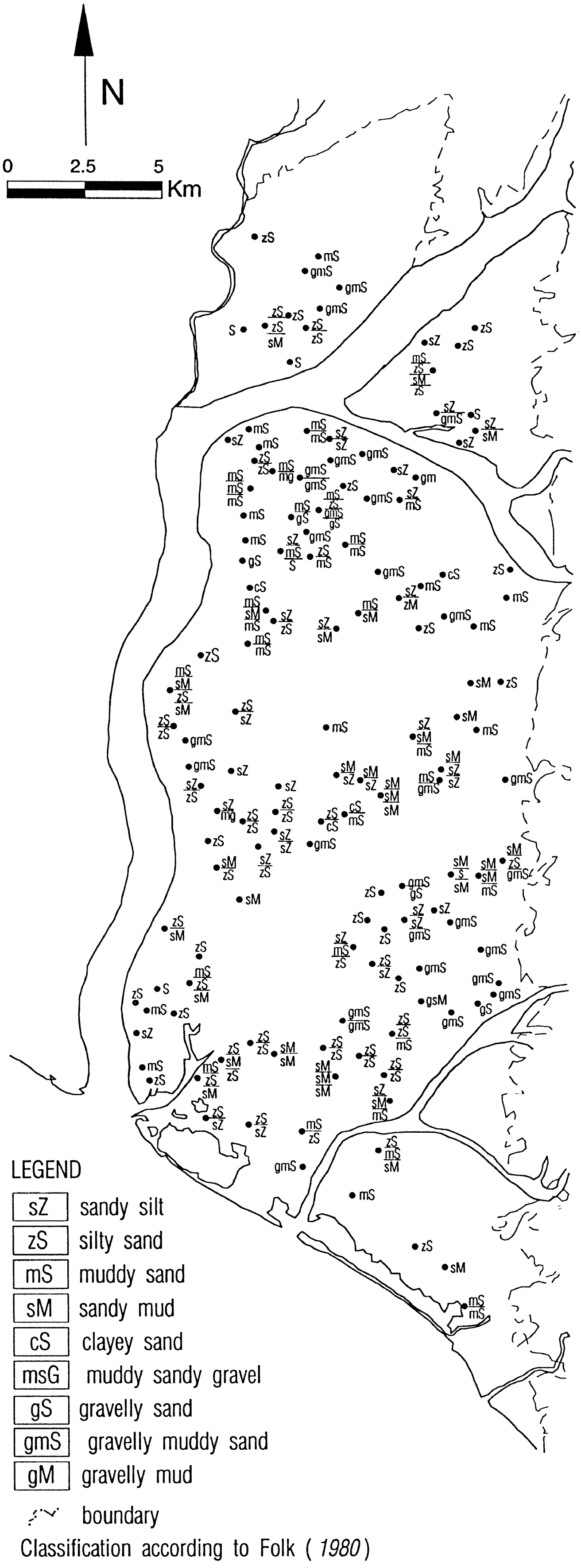


Fig. 4 Soils of Pingtung Plain (after general map of soils in Taiwan published by the Council of Agriculture, 1988)

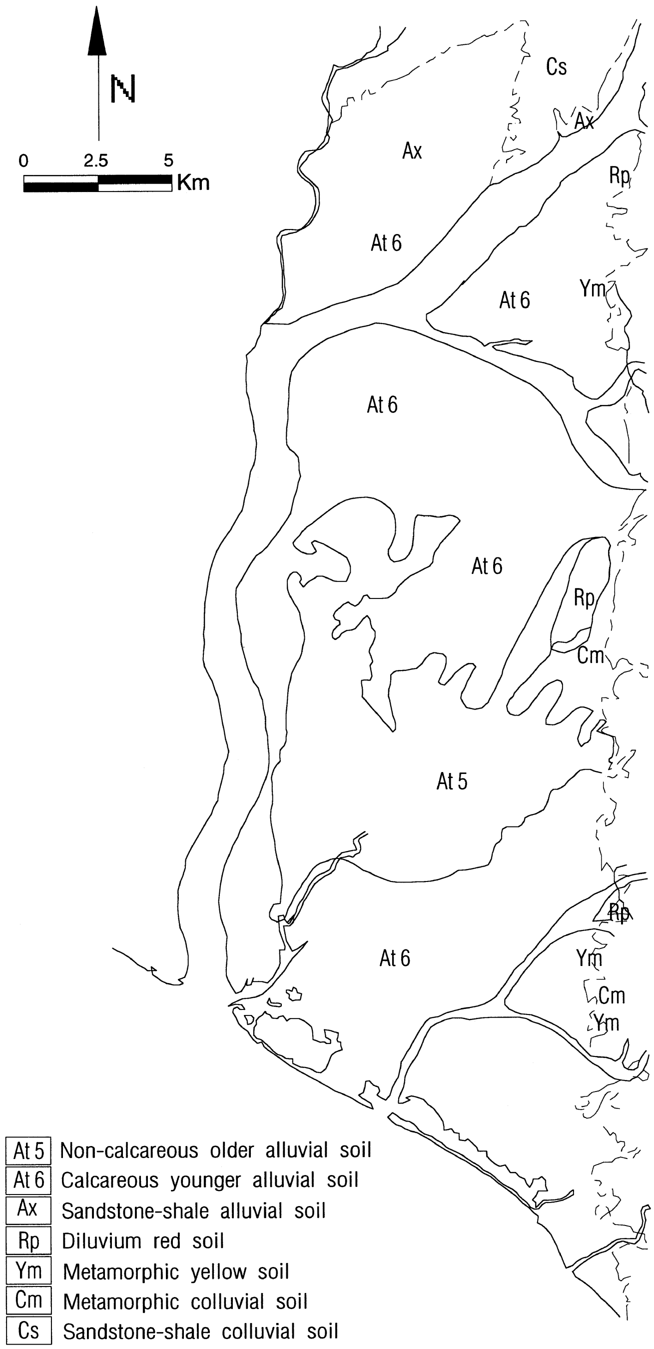


Fig. 5 Soil textures of the Pingtung Plain. (After Jean 1992)

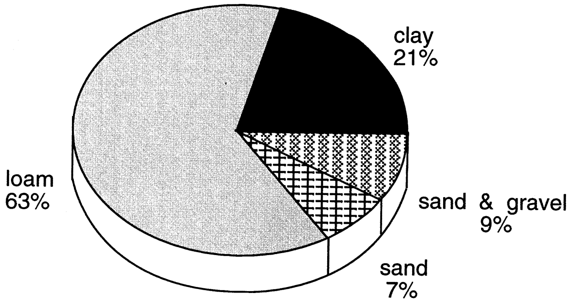


Fig. 6 Distribution of texture in Kaoping River basin

in groundwater as measured in samples from tubewells. Assuming chloride to be a conservative ion and rain water and aerosols to be the only source of chloride (Cl), conservation of mass leads to a relation between precipitation and recharge:

$$P_{eff} \times Cl_p = R \times Cl_{gw} \quad (1)$$

where P_{eff} is the effective precipitation (mm; yearly average); Cl_p is the chloride concentration of precipitation, including dry deposition (ppm; yearly average); R is the recharge (mm/yr); and Cl_{gw} is the constant chloride concentration of groundwater (ppm).

Effective precipitation is used in Eq (1) because in Taiwan most precipitation falls during the summer typhoon season, when extremely high rainfall intensities occur. A large part (about 90%) of this rainfall runs off by overland flow in the Pingtung Plain (Ting 1993). When using Cl_{sm} (the chloride concentration of soil moisture), diffuse recharge is estimated, and when using Cl_{gw}, total recharge is estimated. Using Cl_{gw} is more complicated, because more knowledge is required about the groundwater flow path upstream and other sources of chloride along the path. If Cl_{sm} approximates Cl_{gw}, one can assume that diffuse recharge is the only recharge component. If Cl_{sm} is higher, then a by-pass component may exist in the groundwater recharge process. If recharge is assumed to be equal to effective precipitation minus evapotranspiration, Eq (1) can be rewritten as follows:

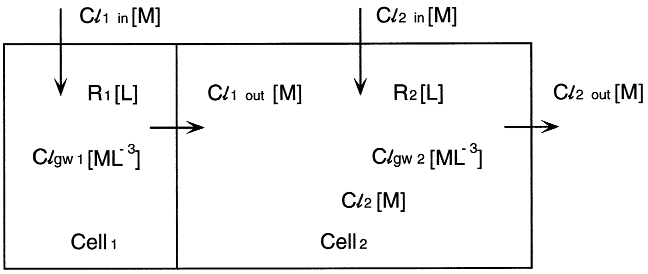
$$Cl_{sm}/Cl_p = P_{eff}/R = P_{eff}/(P_{eff}–Et) \quad (2)$$

where ET is the annual evapotranspiration (mm/yr) and $(P_{eff}–E)$ is the annual recharge (mm/yr).

Evapotranspiration is assumed to be the only process influencing the chloride concentration in soil moisture. The evapotranspiration factor can be calculated if the chloride concentration in precipitation (wet deposition) coincides with the actual chloride deposition (total deposition). The drawback of the Eriksson method is the uncertainty in the determination of the wet and especially the dry deposition. Errors in the determination are mainly due to impingement of sea-salt particles on leaves, fine stems, and branches of vegetation. Chloride deposition can be measured by collecting rainfall at ground level in vegetation stands. In the study area, the land is used mainly for cultivation of crops such as paddy rice, sugarcane, and fish ponds. Sharma and Hughes (1985) introduced a model that includes bypass flow. By assuming by-pass flow to be so rapid that it is not available for root uptake, recharge can be described as:

$$R_{tot} \times Cl_{gw} = R_d \times Cl_{sm} + R_{bp} \times Cl_{bp} \quad (3)$$

where R_{tot} is the total recharge (mm/yr); R_d is the recharge by diffuse flow (mm/yr); R_{bp} is the recharge by localized flow along preferred paths (mm/yr); and Cl_{bp} is the concentration of the preferred flow (ppm), taken as the average chloride concentration in precipitation ($Cl_{bp} = Cl_p$).



$Cl_{1,2\ in}$ [M]	Total input of chloride into Cell 1,2
$R_{1,2}$ [L]	Rainfall amount in Cell 1,2
$Cl_{gw\ 1,2}$ [ML^{-3}]	Chloride concentration of groundwater in Cell 1,2
$Cl_{1,2\ out}$ [M]	Total output of chloride from Cell 1,2

Fig. 7 Mixing-cell model for the chloride mass balance

Also valid is:

$$R_{tot} = R_d + R_{bp} \tag{4}$$

In the Pingtung Plain, irrigation may also contribute to recharge. For this case, Eq (1) is modified to:

$$P_{eff} \times Cl_p + I_r \times Cl_i = R \times Cl_{sm/gw} \tag{5}$$

where I_r is the yearly average irrigation (mm/yr); and Cl_i is the yearly average chloride concentration of irrigation water (ppm). If irrigation is included in Eq (3), the following relation can be derived:

$$R_{tot} \times Cl_{gw} = R_d \times Cl_{sm} + R_{bp} \times Cl_{bp} + R_{ibp} \times Cl_{ibp} \tag{6}$$

where R_{ibp} is the recharge from irrigation by localized flow along preferred paths (mm/yr); and Cl_{ibp} is the concentration of the preferred flow of irrigation water (ppm), taken as the average chloride concentration of irrigation water ($Cl_{ibp} = Cl_i$).

Mixing-Cell Method

A current approach, namely the mixing-cell method (Gieske and De Vries 1990) for the saturated zone, takes into account the subsurface inflow and outflow of chloride and water to calculate the total recharge to the aquifer. The regional groundwater flow is thought to pass from area I through II and III to area IV, which are represented by sites I to IV. In each area, an input of chloride can be considered from precipitation on that area supplemented by an input from the upstream area. This model calculates the chloride balance according to the following equations, as illustrated in *Figure 7*:

Area I (Cell 1):

$$Cl_{\mathrm{I}\ in} = P_{\mathrm{I}} \times Cl_{p\ \mathrm{I}} \times A_{\mathrm{I}}$$
$$Cl_{\mathrm{I}\ out} = Cl_{\mathrm{II}\ in}$$
$$R_{\mathrm{I}} = P_{\mathrm{I}} \times Cl_{p\ \mathrm{I}} / Cl_{gw\ \mathrm{I}} \tag{7}$$

Area II (Cell 2):

$$Cl_{\mathrm{II}\ in} = P_{\mathrm{II}} \times Cl_{p\ \mathrm{II}} \times A_{\mathrm{II}}$$
$$Cl_{\mathrm{II}\ out} = Cl_{\mathrm{I}\ out} + Cl_{\mathrm{II}\ in}$$
$$R_{\mathrm{I}} + R_{\mathrm{II}} = Cl_{\mathrm{II}\ out} / Cl_{gw\ \mathrm{II}} \tag{8}$$

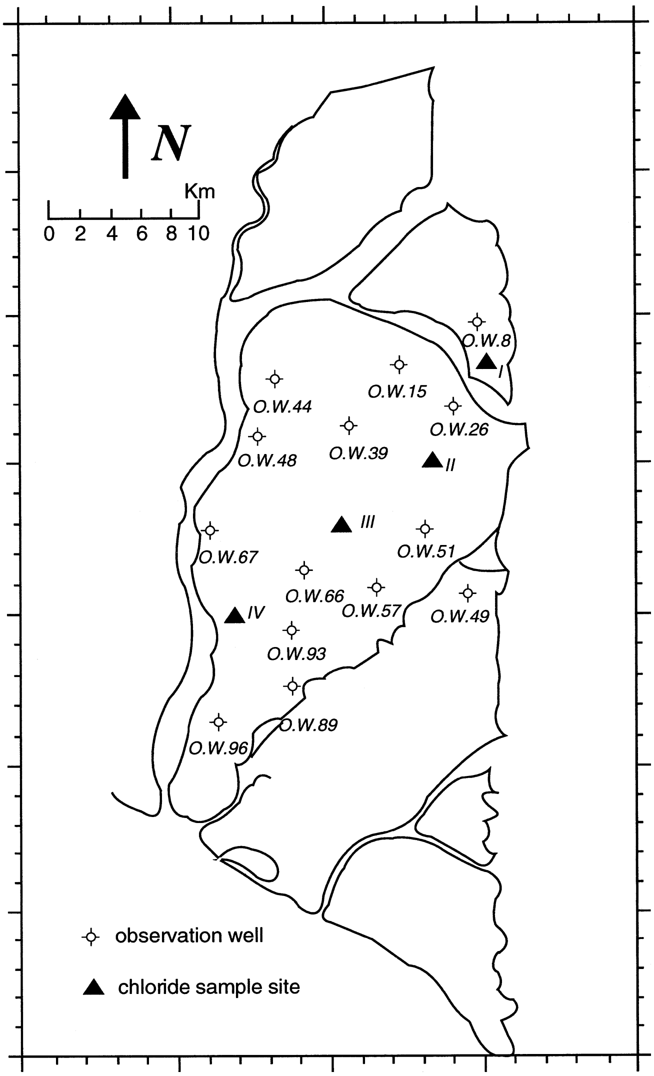


Fig. 8 Locations of chloride sampling sites

Area III (Cell 3):

$$Cl_{\mathrm{III}\ in} = P_{\mathrm{III}} \times Cl_{p\ \mathrm{III}} \times A_{\mathrm{III}}$$
$$Cl_{\mathrm{III}\ out} = Cl_{\mathrm{II}\ out} + Cl_{\mathrm{III}\ in}$$
$$R_{\mathrm{I}} + R_{\mathrm{II}} + R_{\mathrm{III}} = Cl_{\mathrm{III}\ out} / Cl_{gw\ \mathrm{III}} \tag{9}$$

Area IV (Cell 4):

$$Cl_{\mathrm{IV}\ in} = P_{\mathrm{IV}} \times Cl_{p\ \mathrm{IV}} \times A_{\mathrm{IV}}$$
$$Cl_{\mathrm{IV}\ out} = Cl_{\mathrm{III}\ out} + Cl_{\mathrm{IV}\ in}$$
$$R_{\mathrm{I}} + R_{\mathrm{II}} + R_{\mathrm{III}} + R_{\mathrm{IV}} = Cl_{\mathrm{IV}\ out} / Cl_{gw\ \mathrm{IV}} \tag{10}$$

Locations of chloride sampling sites I–IV are shown in *Figure 8*.

Data Collection and Analysis

Sampling and Analysis Techniques

Four sampling sites were chosen on a section running southwest from the Ailiao River to Pingtung. Along the section, deposits grade from the coarse sediments of the alluvial fan near the mountains to the finer deposits along the Kaoping River. Also shown in *Figure 8* are the 11 borehole stations of the Bureau of Water Resources. The section runs parallel to the direction of regional groundwater flow. Three of the four boreholes were drilled using the cable-tool method during the dry season, on 13 and 14 October 1994. At the first site, drilling appeared to be impossible due to the extremely coarse material. After the boreholes were drilled at the other sites, a PVC casing was installed to prevent collapse of the site and to enable later use of a capacitance probe. Soil cores were taken at fixed intervals until the water table was reached. For the depths of 0–1, 1–2, 2–3, and greater than 4 m, the intervals were 0.10, 0.20, 0.25, and 0.50 m, respectively.

The bulk samples at each interval were collected in plastic bags to prevent evaporation, and soil moisture was extracted from the samples by dilution in the laboratory of the Department of Environmental Protection of the NPUST. Chloride content was measured by the Ion Chromatograph and $AgNO_3$ titration. The latter method appeared to be insufficiently accurate because of the low chloride concentrations in the samples and difficulties with visual interpretation of the titration. Therefore, only the results of the Ion Chromatograph were used for this study. The grain-size distribution of each sample was determined by the Department of Civil Engineering, NPUST, using the Unified Classification System (ASTM 1982).

The soil-moisture content of each sample was gravimetrically determined by subtracting the weight after drying from the weight before drying in an oven at a temperature of 105 °C for 24 h. Soil moisture was measured at later stages with a IH1 type Didcot capacitance probe. Average monthly rainfall and evapotranspiration in 1994 for the various sites were determined by a Thiessen polygon-weighting method, including records of 11 stations in the Pingtung Plain maintained by the Bureau of Water Resources. The calculated values for rainfall are shown in *Table 1* for each site, representing the four areas shown in *Figure 8*.

Cl^- concentrations in rainfall were measured at the same stations from May through September in the rainy season, but showed high variability in time and space. Dry deposition was measured on the roof of the faculty of Civil Engineering of the NPUST by a bulk sampler. *Table 2* shows the chloride concentration of the rainfall.

The chloride concentrations of the groundwater were observed by the Bureau of Water Resources at each observation well in April and October. Both values were averaged to obtain the chloride concentration of groundwater, which is shown in *Table 3*. Average chloride concentrations in rainfall for the sites show a steady increase toward the coastal area. Chloride concentration in water from an irrigation channel was determined near site I and was approximately equal to the concentration in rainfall at this site.

Table 1 Weighted monthly precipitation (mm), 1994

Month	Site			
	I	II	III	IV
January	15.7	15.8	18.6	18.5
February	50.5	29.7	25.9	23.8
March	39.5	24.2	22.7	19.7
April	9.8	25.9	43.6	52.1
May	393.0	210.1	200.2	175.6
June	247.1	292.9	328.8	336.7
July	307.5	338.6	372.2	354.1
August	915.5	943.7	1073.8	1090.1
September	186.0	193.5	145.8	137.9
October	7.8	22.0	0.7	0.7
November	0	0	0	0
December	4.3	1.0	4.9	9.5
Total	2176	2096	2237	2218

Table 2 Chloride concentration in precipitation (ppm), 1994

Month	Site			
	I	II	III	IV
May	1.88	0.99	1.07	0.82
June	0.39	0.47	1.16	1.22
July	0.95	1.32	1.04	0.74
August	0.57	1.16	3.06	3.71
September	0.71	0.83	1.28	4.46
Average	0.90	0.95	1.52	2.19
σ (b=5)	0.52	0.29	0.77	1.57

Table 3 Chloride concentration of groundwater (ppm)

Month	Site			
	I	II	III	IV
April	2.8	5.5	14.0	30.0
October	2.9	7.0	23.0	36.9
Average	2.9	6.3	18.5	33.4

Site Descriptions

Table 4 describes the lithology of the four sites; in the following, these sites are described according to the topography, land use, and subsoil.

Site I is located near the Ailiao River in a mango orchard irrigated by sprinklers. Irrigation water is water diverted from the Ailiao River with a chloride concentration of 3.56 ppm. Soil moisture at the site is influenced by the sprinklers, which operate at 5-m spacing. The sampling of soil moisture at this site occurred by excavation of a 2-m^2 pit, because the material was too coarse to be penetrated by the cable-tool method or any other drilling apparatus. Samples were taken at 10-cm intervals. Very coarse gravel or cobbles occur throughout the entire depth, with a sandy-loam layer containing 60% gravel at a depth of 20–30 cm. At a depth of 450 cm, sandy clay loam occurs.

Table 4 Lithology at sites I–IV

Depth (m)	Site			
	I	II	III	IV
0.0–0.1	G	SiL	SiL	SL
0.2–0.3	SL	L	SiL	L
0.4–0.5	G	L	L	SL
0.6–0.7	G	L	L	LS
0.8–0.9	G	fSL	SiC	LS
1.0–1.2	G	fSL	SiC	LS
1.4–1.6	G	LfS	SiC	LS
1.8–2.0	G	LfS	SL	S
2.25–2.50	G	LfS	fSL	S
2.75–3.00	G	SL	SL	S
3.25–3.50	Cb	Cb	VFSL	
3.75–4.00	G			
4.50–5.00	G			
5.00–5.50	SCL			

* SiC = Silty Clay S = Loamy Sand SL = Sandy Loam fSL = fine Sandy Loam VfSL = Very fine Sandy Loam G = Gravel L = Loam S = Sand C = Clay Cb = Cobble

Site II is on an open field underlain by gravel and near the square of a Buddhist temple near the village of Changchih. Nearby are irrigated fields of wax-apple and betel palms intercropped with maize. Irrigation water is directed from the Ailiao River, but groundwater is also used. The profile is not influenced by irrigation, and the lithological log shows loamy material in the upper 50 cm; gravel content ranges from 10–70%. Below this zone, the loam gradually becomes coarser, from fine sandy loam to loamy fine sand. The total depth is 325 cm.

Site III is in the back of a courtyard near Pingtung; the yard is covered by weeds and litter. Irrigated fields of betel palms and bamboo are nearby; the orchards are irrigated from local wells. The site is probably not influenced by irrigation water. The lithology is silt loam to 70 cm, changing into silt clay to 160 cm, and becoming coarser to 350 cm, with fine sandy loam and very fine sandy loam.

Site IV is in the corner of a field of fodder grass near a housing area in the village of Wantan. The site itself is not irrigated and no agricultural practices have occurred recently. The subsoil contains sandy loam and loamy sand to 225 cm, grading into sand at a depth of 450 cm.

Results

Chloride Mass Balance

To calculate diffuse or by-pass recharge, the annual weighted precipitation was used for each site, together with the chloride concentrations of the soil moisture. For site I, Eqs (1) and (5) were used to account for the chloride input from irrigation water, which was 307 mm for the mangos. For sites II and III, Eqs (3) and (4) were used to calculate the ratio of diffuse flow to by-pass flow ($Cl_{sm} > Cl_{gw}$). Total recharge was calculated with Eq (1) and the chloride concentrations of the groundwater. Results are shown in *Table 5*.

Results at Site I, with its coarse texture, confirm the expected high recharge capacity with or without additional irrigation water. Furthermore, recharge rates decrease from sites I to III. This decrease is probably because of the textural change from the coarse sediments along the foothill (site I) to the finer sediments farther from the Central Mountain Range (sites II and III). Site IV, near the Kaoping River, has a coarse texture and a high recharge potential in the upper profile but is presumably located in a discharge area. The infiltrated water is possibly lost by shallow drainage to nearby ditches or canals. The total recharge at Site IV is about 7% of rainfall.

Mixing-Cell Method

Table 6 shows the results of recharge calculations using the mixing-cell method. Actual recharge to the groundwater in the Pingtung Plain is restricted to the areas

Table 5 Chloride mass balance

Site	Chloride concentration (ppm)				Diffuse recharge (mm)	Total recharge (mm)	Precipitation, P (mm/yr)	Irrigation (mm/yr)	R_{bp}/R_d
	Soil moisture, Cl_{sm}	Groundwater, Cl_{gw}	Precipitation, Cl_p	Irrigation water, Cl_{irr}					
I	2.9	2.9	0.90	–	676 (31%)	676 (31%)	2177	–	–
$I_{irr} + I_p$	–	2.9	0.90	3.6	1057 (48%)	–	2177	307	–
II	8.3	6.3	0.95	–	240 (11%)	316 (15%)	2096	–	9.8
III	22.8	18.5	1.52	–	149 (7%)	184 (8%)	2237	–	2.4
IV	3.8	33.4	2.19	–	1279 (58%)	145 (7%)	2219	–	–

Table 6 Mixing-cell method

Site	A (km^2)	Cl$_{gw}$ (ppm)	Cl$_p$ (ppm)	P (mm)	Cl$_{in}$ ($\times 10^6$ mol)	Cl$_{out}$ ($\times 10^6$ mol)	R (mm/year)
I	28	2.9	0.9	2177	55	55	685
II	81	6.3	1.0	2096	161	216	188
III	130.5	18.5	1.5	2237	444	660	10
IV	27	33.4	2.2	2219	131	791	−446

represented by sites I and II. The groundwater flow mechanisms in areas III and IV appear to be negligible. Site IV represents the discharge area near the Kaoping River, and although the coarse texture allows a high input of irrigation water and rainfall to the topsoil, it probably does not contribute to the underlying aquifer. Upward hydraulic gradients that occur in that area also preclude the possibility of recharge. Water that infiltrates into the top layer is discharged via nearby ditches or canals and does not contribute to the groundwater body.

Comparison of Results

Chloride mass-balance estimates were made for sites with bare or sparsely vegetated land without irrigation (except for site I). These conditions result in lower recharge rates estimated by this method compared with the soil water-budget calculations. For fallow land without irrigation, a recharge rate of 553 mm was derived from the decadal budget (Ting 1996). This value is high when compared with the recharge rates calculated by the chloride mass-balance method. In order to arrive at a reliable input of recharge for a groundwater model, it is necessary to determine the boundaries of recharge and discharge areas. In areas I and II, recharge probably is 10–30% of the annual rainfall, excluding recharge from additional irrigation water.

Conclusions and Recommendations

The chloride mass-balance method was used to estimate groundwater recharge in the Pingtung Plain, Taiwan. From the obtained results, the following statements are made:

1. Recharge in the Pingtung Plain is unevenly distributed. Potential recharge is high in sites I and II, but is negligible at sites III and IV, in downslope positions.
2. Along the foothills of the Central Mountain Range (site I), recharge rate is the highest (685 mm, or 30% of the annual rainfall). When recharge from irrigation water is considered as well, recharge is nearly 50% of precipitation. Farther downslope, recharge rates decrease to 5–20% of the annual rainfall, whereas near the Kaoping River, recharge becomes zero.
3. The locations of the four sites for the chloride mass-balance analysis were not optimally chosen. It is uncertain that they were absolutely not influenced by nearby irrigation works. Where irrigation was applied on the site, the amount and exact chloride content of irrigation water was unknown. Site IV was influenced by saltwater intrusion or by another source of chloride, which invalidates calculation of recharge using the chloride content of the soil moisture.
4. Chloride mass-balance analysis should be performed for more sites throughout the plain. Because most of the land is cultivated and under irrigation, the sites should be chosen on agricultural fields. This approach requires a careful determination of irrigation application and monitoring of chloride inputs from irrigation water, pesticides, and fertilizers. The sites should be chosen on soils with different texture in sections that are parallel to the prevailing flowlines, preferably in uniform, non-polluted areas unaffected by brackish-water influences.
5. Groundwater recharge as a source of pollution by fertilizers or pesticides is likely to become an important topic for research in the near future.
6. A study on the indirect recharge from river beds might reveal the importance of this component with respect to the total groundwater reserves of the Pingtung Plain. Considering the very coarse texture of deposits underlying these areas, especially in the proximal fan, considerable recharge probably occurs.

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