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The evaluation of groundwater environmental restoration by artificial recharge in Pingtung Plain, Taiwan

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Abstract Pingtung Plain has abundant groundwater resources. The overall study objective focuses on groundwater restoration. In this study, MODFLOW was applied to evaluate the groundwater recharge dynamics between the recharge in the upstream reaches and pumping in the downstream reaches. Using the simulation model, the results show that storage of the groundwater increased by 683 266 m^3/year and 2 471 765 m^3/year and the groundwater table has risen 0.91 m and 1.21 m in Kaoping Lake and Wanlung Lake, respectively. From the view of STORAGE Change, the Wanlung Lake was found to be the most suitable area for constructing the artificial lake for artificial recharge. The variation of the groundwater storage of the aquifer is an important factor in artificial recharge. Managing artificial groundwater recharge can provide for shortages of good quality surface water during flood season, caused by higher turbidity, and conjunctive water use of surface and groundwater resources in the future.

Keywords artificial recharge of groundwater; MODFLOW; simulation

INTRODUCTION

Pingtung Plain is located in southern Taiwan and extends approximately 1210 km^2.There is a very high annual rainfall in this area; however, the amount of rainfall received varies significantly over the course of the year. In terms of measurement data, 90% of the annual precipitation falls during the rainy season (i.e. May to September) while only 10% of the rainfall occurs during the dry season (October to April). This uneven distribution in the monthly rainfall poses a major problem to the planners involved in the protection and utilization of water resources in Pingtung Plain. As a result of the hypsographical variation, the water resources are not readily stored into aquifer, but tend to flow rapidly into the ocean. Consequently, the utilization rate of surface water resources is limited in Taiwan. However, the thriving aquaculture found along the southwestern coastal areas of Taiwan is dependent on availability of abundant freshwater. In most cases, this freshwater has been supplied by the intensive pumping of groundwater. This has led to a drop in the local groundwater level, and in severe cases has resulted in land subsidence and seawater intrusion.

The results of previous studies in artificial recharge of groundwater have indicated that the groundwater environment can be improved and restored (Bouwer, 1999; Ting *et al.*, 2002; CTCI, 2002; Yang, 2006). The overall study objective focuses on groundwater restoration. In this study, MODFLOW was applied to evaluate the groundwater recharge dynamics between the recharge in the upstream reaches and pumping in the downstream reaches.

STUDY AREA AND METHODOLOGY

Geographical location

Pingtung Plain is located in southern Taiwan. There are nine groundwater sub-regions from north to south, and these are mostly in the south (SRWRO, 2005). It mainly comprises the flat area of the catchments of the Kaoping, Tungkang and Linpeing rivers. The regional area covers in total 25 counties in Pingtung and Kaohsiung cities. This elongated plain covers an area of 1210 km^2, being 22 km wide in an east–west direction and 55 km long the north–south direction. The groundwater sub-region of Pingtung Plain is mainly in the east and close to the Central Mountain (Fig. 1).

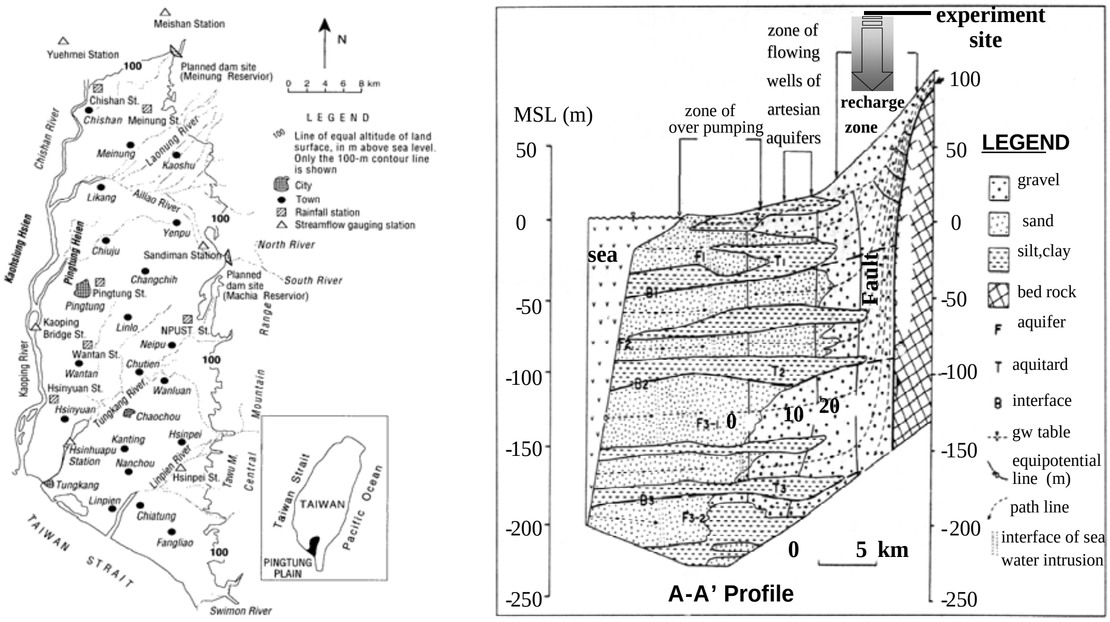


Fig. 1 Location of study area in Pingtung Plain, Taiwan, and geological profile (Ting, 1997).

Climatic regime

The climate of Pingtung Plain is sub-tropical; rainfall is alternately affected by typhoons in summer, producing most of the rainfall. The rainy seasons lasts from May to September. The groundwater of Pingtung Plain mainly comes from rainfall then through infiltration into the aquifer in the mountains and, consequently, the groundwater table is higher during the rainy .

The maximum average rainfall is 3146 mm, 2980 mm, 2246 mm, 2152 mm, 2249 mm and 2460 mm in the Laonung, Ailliao, Chishan, Kaoping, Tungkang and Linpien river basins, respectively. The maximum average wind speed is 5.0 m/s in November and the minimum is 2.6 m/sec. Average annual temperature in Pingtung is 25.2°C. Average annual evaporation is about 1723 mm.

Surface water

The Pingtung Plain mainly comprises flat areas of the Koaping, Tungkang and Linpien river catchments, as well as several small streams; the three main rivers finally flow into the Taiwan Strait. In the *Yearbook of Hydrology* (Water Resources Agency, 2007) the Ministry of Economic Affairs show the average annual discharges as approx. 6330 Mm^3 for Koaping River, 952 Mm^3 for Tungkang River and 728Mm^3 for Linpien River. Other parameters are given in Table 1.

In this study, MODFLOW was applied to evaluate the groundwater recharge dynamics between the recharge in the upstream reaches and pumping in the downstream reaches. The results from groundwater model are then used to manage and deploy the water resources of Pingtung Plain, as below:

Table 1 River and hydrological characteristics in Pingtung Plain (WRA, 2007).

River	Inflow Location	Elevation (m)	Outflow location	Length (km)	Average slope	Basin area (km^2)	Average rainfall (mm)	Average discharge (Mm^3)
Koaping	Mt. Morrison	3997	Hsinyuan	171	1/150	3 256	2 547	6 330
Tungkang	Ailliao	1138	Tungkang	44	1/500	472	2 093	952
Linpien	Central Mt.	2880	Linpien	42	1/15	344	3 314	728

Model description

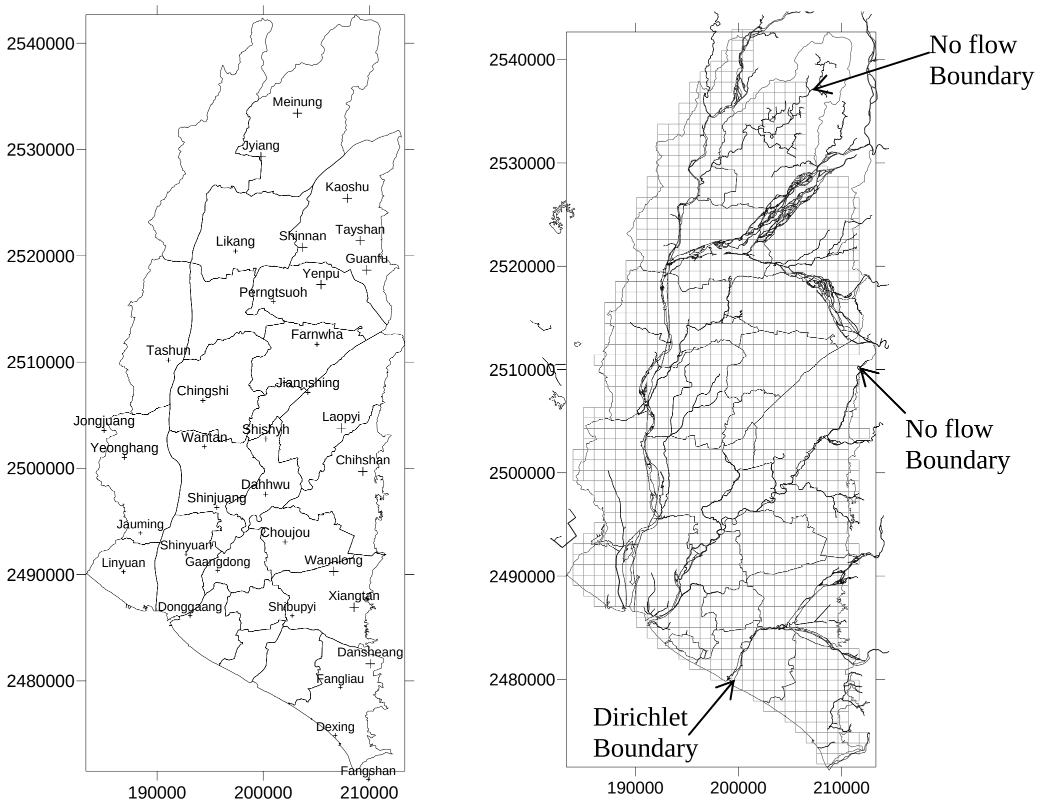
Defining a conceptual structure of the groundwater system is a necessary prerequisite to numerical simulation **(**SRWRO, 2007). The main purpose is to simplify the field problem and frame the associated field data, through the conceptual model to create a rational quantification with hydrogeology and hydrological stresses (Ting, 1997). The hydrological stresses which need to be considered when simulating groundwater flow in the plain, such as: abstraction from wells, precipitation, recharge,interaction with river, evapotranspiration and boundary condition.

Model construction

An important tool to characterize the aquifer is its hydrogeological profile, which was prepared for by the central Geological Survey and Ministry of Economic Affairs, WRA. (2001). Figure 2 shows the observation wells; in total there are 52 aquifer monitoring stations and 127 wells set up in Pingtung Plain which provide the hydrogeological and observation data for the conceptual model.

Model grid and aquifer system

There are seven layered hydrogeological units in the aquifer, reaching down to about 220 m depth, to relate to the aquifer system data (Table 2) and observation wells as Fig.2 (a). Actually, the conceptual model can be simplified into a three-layer system: the first layer was defined as unconfined aquifer, and the second and third were defined as unconfined/confined interactive aquifer. Based on data availability and hydrogeological conditions, the grid spacing in both the x and y directions is 1000 m. The aquifer system is bounded by mountains in the north and east, by Funshin Hill in the west and by Taiwan Strait in the south as Fig. 2 (b).



(a).observation wells (b). boundary conditions

Fig. 2 Location of observation wells and boundary conditions in Pingtung Plain.

Table 2 The depth of hydrogeological layers in study area (unit: m).

Toponym	Layer: F1	T1	F2	T2	F3-1	T3	F3-2
Linyan	44.5	22	14.5	24	68	0	57
Sipu	37	13	54	10	52	0	0
Jongjuang	54.5	0	65.5	0	78	6	6
Chingsi	47.5	0	57.5	4	89	6	6
Datan	40	5.5	44.5	15	70	7	48
Sinjhuang	31	27	43	0	81	0	28
Likang	44.5	0	79.5	0	81	0	5
Wanluan	53.5	5	54.5	13.5	49.5	22	12
Jiansing	51	0	64	0	83	3	11
Xishi	36.5	8.5	63	0	65.5	16	21.5
Shibupyi	23.5	23.5	45.5	23	62.5	18	15
Wannlong	80.5	6.5	50.5	0	72.5	0	0
Shinuan	26.5	18.5	38	12	80	0	35
Keefung	30	19	42	10	83.5	0	45.5
Majia	83.5	0	62.5	0	64	0	0
Chanliao	57	0	47	0	57.5	19	39.5
Yeonghang	62	0	41.5	6	70.5	4	36
Chunchou	43	0	79.5	0	82.5	0	15
Meinung	43	0	27	0	0	0	0
Haifong	52.5	0	62.5	0	89	6	10
Choujou	27	31.5	47.5	0	74	0	40
Konggang	33	29	22.5	16.5	73	0	46
Wantan	52	0	48	4.5	70	25.5	20
JiuRu	47	0	65	8	84	0	16
Yenpu	65	0	67	0	78	0	0
Kaoshu	80	0	72	0	46	0	0
Tayshan	65	0	70	0	75	0	0
Nei-Pu	45	7.5	59.5	0	68	7	23
Laopi	45	10.5	61.5	0	73	0	20
Dansheang	86	0	9	0	0	0	0
Dansheang	67	9.5	59.5	0	4	0	0
Fangshan	73	0	51	0	80	10	6
TaChung	47.5	8.5	51	0	84	0	29
Kanding	37.5	17.5	30	23.5	76.5	0	35
Fangshan	36	0	0	0	0	0	0

RESULTS AND SIMULATION

Water balance

The results of the water budget are given in Table 3. In term of the results, the well abstraction was approx. 1330 Mm^3/year. The river leakage into the aquifer was approx. 201 Mm^3/year, and the aquifer outflow to the river was approx. 167 Mm^3/year. The water balance clearly indicates that recharge is principally derived from precipitation on the plain and lateral inflow from numerous mountains and slopes during the rainy period.

Case study

The purpose of the case studies is evaluation of recharge so that we obtain the best simulations for the well abstraction study. Because of the artificial recharge of groundwater in the upstream area, the groundwater can be used downstream. The sites chosen for simulation are Kaoping Lake site and Wanlong Lake site, as shown Fig. 3.

Table 3 Groundwater balances for Pingtung Plain in 2000 (m^3/year).

-	Inflow	Outflow
Storage Change	827 284 670	889 898 716
Outside area	16 660 865	7 395 217
Well abstraction	0	1 338 587 726
Lateral inflow mountain	959 322 179	0
Precipitation	447 691 061	0
Evapotranspiration	0	48 501 500
River exchange	201 306 593	167 298 860
Total	2 452 265 369	2 451 682 019

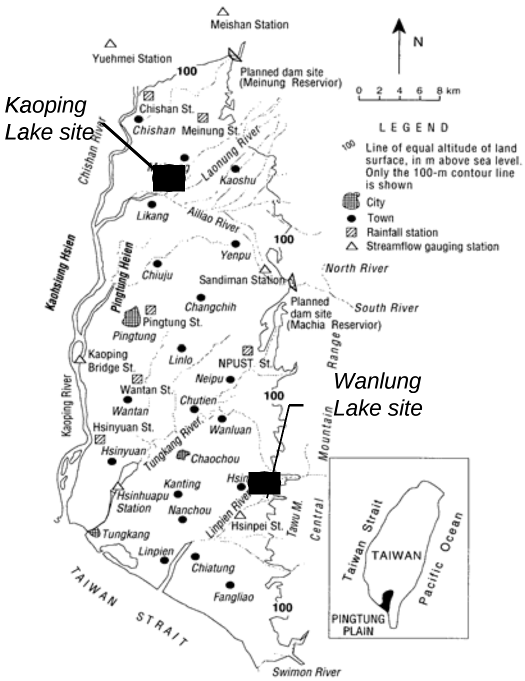


Fig. 3 Locations of the Kaoping Lake and Wanlung Lake.

Case study A

In study A, the hypothesis is of artificial recharge in the rainy season (June to August) on Kaoping Lake; the simulation condition was 345 000 m^3/day recharged into aquifer. In addition, these studies hypothesize that there are two flow lines of aspect to analyse water level variation in downstream, then to evaluate the water balance, as shown Fig. 4. The groundwater variation was effected by the artificial recharge, with an average rise of 0.91 m and the aquifer storage increased by 683 266 m^3/year, as shown Table 4 and Fig. 5, respectively.

Case study B

In the case of study B, the hypothesis is implementation of artificial recharge in the rainy season (June–August) on Wanlung Lake; 400 000 m^3/day recharged into the aquifer. In addition, these studies hypothesize that there are three flow lines of aspect to analyze water level variation in downstream, then to evaluate water balance by the way, as shown Fig. 6. The groundwater variation was effected by the artificial recharge; the average rise was 1.21 m and the storage change was an increase of 2 471 765 m^3/year in the aquifer. The results are illustrated in Table 5 and Fig. 7.

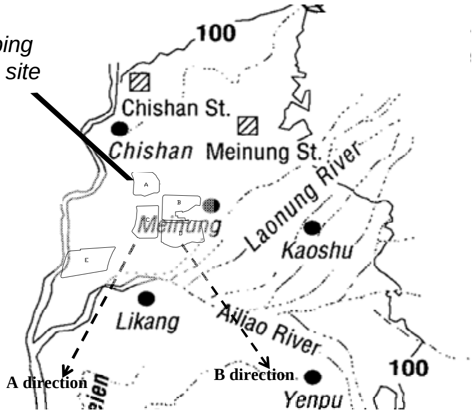


Fig. 4 Location of Kaoping Lake in Pingtung Plain.

Table 4 The variation of groundwater in downstream (unit: m).

Flow lines	Position of observation	June	August	October	December
	Downstream 2000m	1.16	4.43	3.45	2.4
A	Downstream 5000m	0.24	1.01	1.32	1.33
	Downstream 10000m	0.078	0.145	0.285	0.427
	Downstream 2000m	1.66	4.18	2.99	2.22
B	Downstream 5000m	0.065	0.46	0.73	0.79
	Downstream 10000m	0.014	0.024	0.102	0.175

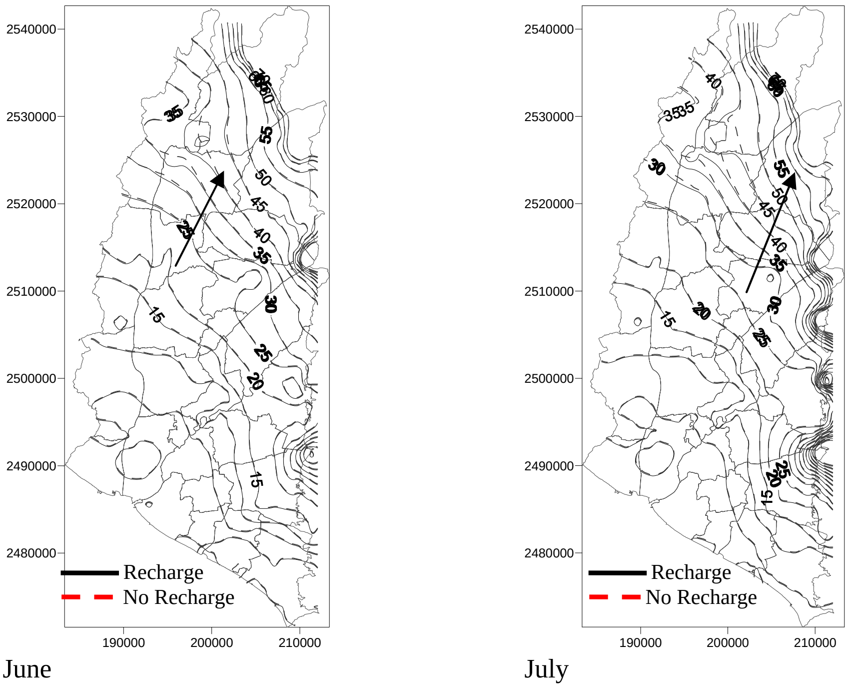


Fig. 5 Contour maps of recharge for layer 1.

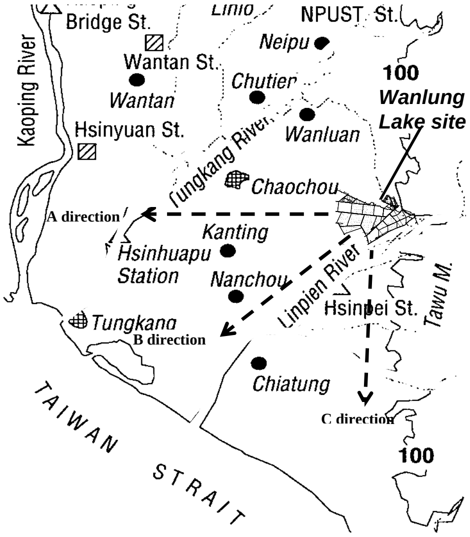
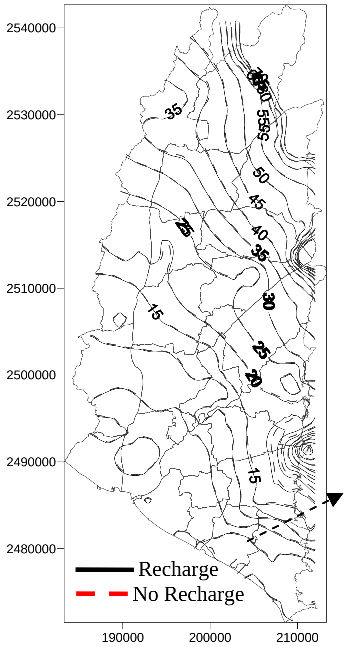


Fig. 6 Location of Wanlung Lake in south of Pingtung Plain.

Table 5 the variation of groundwater in downstream (unit: m)

Flow lines	Position of observation	June	August	October	December
	Downstream 2000m	2.98	3.34	1.62	1.12
A	Downstream 5000m	0.67	1.52	1.23	0.94
	Downstream 10000m	0.0019	0.023	0.073	0.132
	Downstream 2000m	1.91	2.45	1.51	1.09
B	Downstream 5000m	0.06	0.38	0.59	0.64
	Downstream 10000m	0.0012	0.009	0.026	0.05
	Downstream 2000m	3.02	2.85	1.65	1.15
C	Downstream 5000m	0.34	1.0	1.04	0.93
	Downstream 10000m	0.05	0.23	0.35	0.41



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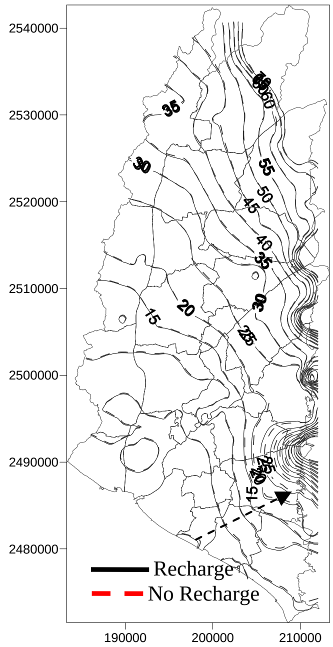

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Fig. 7 Contour maps of recharge for layer 1.

CONCLUSIONS

Using the simulation model, the results show that the storage of the groundwater increased by 683 266 m^3/year and 2 471 765 m^3/year and groundwater table has risen by 0.91 m and 1.21 m in Kaoping Lake and Wanlung Lake, respectively. From the point of view of storage change, Wanlung Lake was the most suitable area to construct the artificial lake, and more so than Kaoping Lake. The variation of groundwater and storage in the aquifer are important factors in artificial recharge.

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