Climate-induced hydrological impacts on the groundwater system of the Pingtung Plain, Taiwan

Kuo-Chin Hsu · Chung-Ho Wang · Kuan-Chih Chen · Chien-Tai Chen · Kai-Wei Ma

Abstract The Pingtung Plain is one of the most important groundwater-resource areas in southwestern Taiwan. The overexploitation of groundwater in the last two decades has led to serious deterioration in the quantity and quality of groundwater resources in this area. Furthermore, the manifestation of climate change tends to induce the instability of surface-water resources and strengthen the importance of the groundwater resources. Southwestern Taiwan in particular shows decreasing tendencies in both the annual amount of precipitation and annual precipitation days. To effectively manage the groundwater resources of the Pingtung Plain, a numerical modeling approach is adopted to investigate the response of the groundwater system to climate variability. A hydrogeological model is constructed based on the information from geology, hydrogeology, and geochemistry. Applying the linear regression model of precipitation to the next two decades, the modeling result shows that the lowering water level in the proximal fan raises an alarm regarding the decrease of available groundwater in the stress of climate change, and the enlargement of the low-groundwater-level area on the coast signals the deterioration of water quantity and quality in the future. Suitable strategies for water-resource management in response to hydrological impacts of future climatic change are imperative.

Résumé La plaine de Pingtung est l’une des plus importantes zones de ressource en eau souterraine du Sud-Ouest de Taiwan. La surexploitation de l’eau souterraine durant les deux dernières décennies a conduit à une sérieuse détérioration de la quantité et de la qualité des ressources en eau souterraine dans cette zone. De plus, la manifestation des changements climatiques tend à induire une instabilité des ressources en eau souterraine et renforce l’importance des ressources en eau souterraine. Le Sud-Ouest de Taiwan montre, en particulier, des précipitations annuelles et des nombres annuels de jour de pluie à la baisse. Pour gérer efficacement les ressources en eau souterraine de la Plaine de Pingtung, une approche par modélisation numérique est adoptée pour étudier la réponse du système hydrogéologique aux variabilités climatiques. La construction du modèle hydrogéologique est basée sur les informations géologiques, hydrogéologiques et géochimiques. En appliquant le modèle de régression linéaire aux précipitations pour les deux prochaines décades, le résultat de la modélisation montre que la baisse du niveau d’eau atteint un état alarmant au regard de la décroissance des eaux souterraines disponibles et la contrainte du changement climatique, tandis que l’extension de la zone de niveau bas des eaux souterraines à la cote indique une détérioration de la quantité et de la qualité de l’eau dans le futur. Des stratégies convenables pour la gestion des ressources en eau souterraine en réponse aux impacts hydrologiques de futurs changements climatiques sont impératifs.

Resumen La llanura Pingtung constituye uno de los recursos de aguas subterráneas más importantes en el Suroeste de Taiwan. La sobreexplotación de las aguas subterráneas en las dos últimas décadas ha dado lugar a un serio deterioro de la calidad y la cantidad de los recursos subterráneos en esta área. En particular el Suroeste de Taiwan muestra una tendencia decreciente en las cantidades de precipitación y en los días anuales de lluvia. Para gestionar de forma efectiva los recursos subterráneos en la Llanura Pingtung, se ha utilizado un

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modelo numérico aproximado para investigar la respuesta de las aguas subterráneas a la variabilidad climática. Un modelo hidrogeológico se construye a partir de la información geológica, hidrogeológica y geoquímica. Aplicando el modelo de regresión linear de la precipitación para las próximas dos décadas, el modelo resultante muestra que el descenso de los niveles de agua en el abanico proximal es alarmante, observándose el descenso del agua subterránea disponible en la presión del cambio climático, y el crecimiento del área de descensos de niveles de agua subterránea en la costa apunta a un deterioro de la cantidad y calidad del agua subterránea en el futuro. Se imponen pues, estrategias apropiadas para la gestión de los recursos hídricos en respuesta a los impactos hidrológicos del futuro cambio climático.

Keywords Climate change · Numerical modeling · Groundwater management · Pingtung Plain · Taiwan

Introduction

Taiwan has been blessed by abundant precipitation of ~2,500 mm/year, which is 3.5 times the world average annual precipitation. However, due to the significant topographic relief and unevenly distributed rainfall, most of the precipitation becomes runoff and drains to the ocean in a very short time. The available water quota for each person in Taiwan is only one eighth of the world average. Efficient management is very important to sustain the water supply using the very limited water resources.

Due to the shortage of surface water, groundwater is an important water resource in Taiwan. At present, groundwater contributes 34% of the total annual water supply. However, overexploiting the groundwater resources has led to seawater intrusion, land subsidence, lowering of groundwater levels, salinization of soil, and reductions in well yields in Taiwan (TPWCB 1994, 1998). Furthermore, recent meteorological data show that climate change is occurring in Taiwan (Hsu and Chen 2002) and causing significant impact on the hydrological environment (Wang 2004). For example, the average temperature of the last hundred years has risen 1.1°C in Taiwan (Hsu and Chen 2002), which is almost twice the world average. The rate of the rise is uneven and shows a tendency of acceleration in recent years. Just in the last two decades, the average temperature has elevated 1°C. The deviation has also appeared in regards to precipitation in addition to the temperature. On the one hand, drought has become more frequent and longer lasting in recent years. On the other hand, two consecutive over-one-hundred-year-return-period rainfall events happened in 2004 and three strong typhoons hit Taiwan in 2005. These symptoms of climate fluctuation tend to induce instability in the utilization of surface-water resources. With an erratic supply of surface-water resources, it is clear that Taiwan's groundwater resources will be increasingly relied upon in the future. Facing such a crucial challenge, studies of groundwater response under the stress of climate change for the purpose of water-resource management become imperative.

Although climate change has been widely recognized (IPCC 1995, 2001), research on the impacts of climate change on the groundwater system is relatively limited (Allen et al. 2004). The reasons may be that long historical data are required to analyze the characteristics of climate change. These data are not always available. Also, the driving forces that cause such changes are yet unclear. The climatic abnormality may occur frequently and last for a period of time. Recent developments based on the study of ice cores from Antarctica and elsewhere (Alley et al. 2003) suggest that drastic climatic changes from glacial to inter-glacial climates can develop over a period of just a few decades, and that droughts on a continental scale can occur occasionally. Studies on 500-year tree-ring data from the Upper Colorado River Basin (Piechota and Tootle 2004) also indicate that severe droughts had occurred in the past and periods of more than 10-year drought were common. Even if these data exist, uncertainty is embedded in model parameters, structure and driving force of the hydrological cycle (Wagener et al. 2004). Predicting the long-term effect of a dynamic system is very difficult because of limitations inherent in the models, and the unpredictability of the forces that drive the earth (Narasimhan 2005). For example, Hsu and Chen (2002) reported the projected precipitation change in Taiwan using Intergovernmental Panel on Climate Change (IPCC) models. The results of five IPCC models are not consistent. The models show the area-range precipitation change near Taiwan ranging from −0.5 to 0.6 mm/day. To study the response of the groundwater system to the stress of climate change, both long-term meteorological data and a reliable hydrogeological model are required. Iterative modeling may be needed to modify the conceptual model, and uncertainties can be reduced when new data are incorporated in the conceptual model (Bredehoeft 2005).

A physically based model of a groundwater system under possible climate change based on available data is very important to prevent the deterioration of regional water-resource problems in the future. Although uncertainties are inevitable, new response strategies in water-resource management based on the model are useful. This paper explores the possible impact of climate change on the groundwater system of the Pingtung Plain in Taiwan using meteorological data over a 60-year period. The characteristics of precipitation change in Taiwan are introduced first. Then, the basic information including geology, hydroclimate and water use of the Pingtung Plain are described. Methodology including data collection, hydrogeology model construction, recharge estimation, numerical modeling are presented. Modeling results of possible climate impacts on the Pingtung Plain in the next 20 years and assumptions/

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limitations of the adopted approach are discussed and summary and conclusions are given.

Precipitation change patterns in Taiwan

Precipitation is unevenly distributed in Taiwan (WRA 2004). Northern Taiwan receives more precipitation than the other areas. Precipitation is also non-stationary in time. While the ratio of precipitation in the wet season (May to October) to that in the dry season (November to April) is 6:4 in northern Taiwan, this value increases to 8:1 in eastern and central Taiwan and 9:1 in southern Taiwan. Thus, southern Taiwan has the highest contrast between the wet and dry seasons in the country. To explore the characteristics of climate change in Taiwan, precipitation data of 21 meteorological stations in Taiwan over a period of 60 years (1941–2005) were compiled and analyzed.

Taiwan can be sub-divided into three districts (Fig. 1) based on the hydrological divisions: north, southwest and southeast (WRA 2004). There are eight, nine and four stations in the northern, southwestern and southeastern hydrologic districts, respectively (Fig. 1).

Figure 2a shows the variations of the annual precipitation for Taiwan and its three districts from 1941 to 2005. The average precipitation of Taiwan for the last six decades is 2,561 mm with northern Taiwan averaging 3,078 mm and southeastern and southwestern Taiwan averaging only 2,164 and 2,266 mm , respectively. A preliminary analysis using linear regression shows that the annual precipitation in Taiwan decreased only 0.03 mm/year. However, the variations in patterns are more pronounced among the districts. While northern Taiwan has shown an increase of 10.36 mm/year, southwestern Taiwan, in contrast, has a decrease of 7.84 mm/year. The variation of annual precipitation in southeastern Taiwan is mild with a decrease of 3.53 mm/year.

With an average of 157 annual precipitation days, the number of annual precipitation days in Taiwan has also decreased in the last six decades (Fig. 2b).While northern Taiwan has the highest average annual precipitation days (184 days), southwest Taiwan has the lowest average with only 129 annual precipitation days. All three districts show consistently decreasing trends. Southeastern Taiwan has the largest rate of reduction: 0.64 precipitation days/year. Southwestern Taiwan also has a relatively high reduction rate of 0.57 precipitation days/year, while the north experiences a lower reduction of 0.14 days/year.

Precipitation intensity, serving as an index for the extremity of precipitation, is defined as the ratio of annual precipitation amount to annual total of precipitation days. With an average precipitation intensity of 16.2 mm/day, the precipitation intensity of Taiwan has increased in the last six decades as shown in Fig. 2c. Southwestern Taiwan has the largest average precipitation intensity (17.7 mm/day) while southeastern Taiwan has the smallest value of 13.1 mm/day. All three districts show consistently increasing trends. Northern and southeastern Taiwan show increases in precipitation intensity of 0.07 and 0.04 mm/day year^{-1}, respectively, while southwestern Taiwan has the smallest increase rate of 0.02 mm/day.

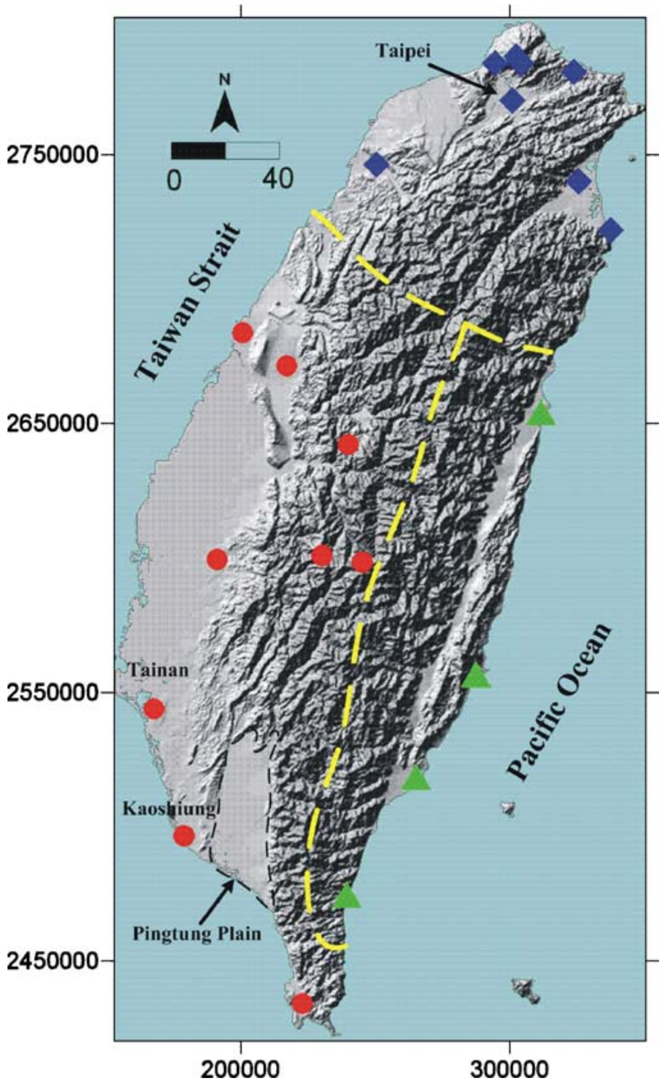

Fig. 1 The 21 meteorological stations in Taiwan (*blue diamonds* northern part, *red circles* southwestern past, and *green triangles* southeastern part) and three hydrological districts separated by *heavy dashed lines*. The locations of the capital city *Taipei* and the study area (*Pingtung Plain*) are also shown

The results of precipitation change indicate very different patterns for the northern and southern districts in Taiwan. They provide an important reference for the efficient utilization of water resources in the future. Northern Taiwan has received a higher precipitation amount and fewer precipitation days in recent years. This phenomenon may result in less reliable surface-water resources because of the limited capacity of existing facilities. For southwestern Taiwan, both the total amount of precipitation and precipitation days show concurrently decreasing trends while the precipitation intensity increases slightly. According to the

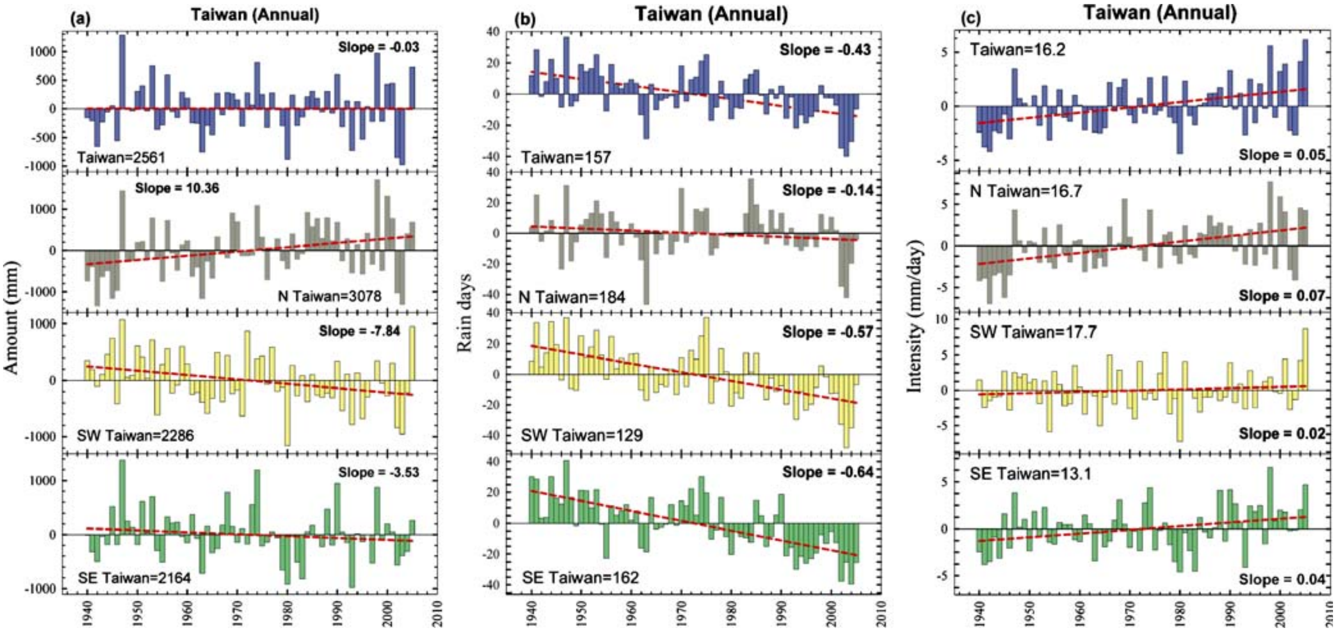

Fig. 2 The variations of Taiwan precipitation patterns: **a** variations of precipitation from the average; **b** variations of precipitation days from the average; **c** variations of precipitation intensity from the average. Average numbers and rate changes are shown in each figure part; *dashed lines* represent the linear regression trends for each plot

precipitation record, southern Taiwan has received less precipitation with a stronger uneven distribution in seasons compared to northern Taiwan. In short, the patterns of precipitation change indicate a worse situation of water resources in southern Taiwan. The amount of available surface water will be less than the average and the existing facilities may be overwhelmed by erratic and very intensive precipitation. If such a change pattern persists, there is one immediate question: How long can the groundwater system sustain the water demand under the stress of climate change? It is clear that groundwater resources will be increasingly relied upon in southwestern Taiwan due to the reduction of surface water in the future. The possible impact of such climate change on the groundwater system is thus the main focus of this paper.

Study area

Location and physiography

The Pingtung Plain with an area of 1,210 km^2 is located in the southwest part of Taiwan (Fig. 1). It is bounded by low hills in the west, foothills in the north, the Central Mountain Range in the east and the Taiwan Strait to the south (Fig. 3). The plain mainly comprises the flat areas of the catchments of the Kaoping, Tungkang, and Linpien rivers. These rivers form a natural discharge base for regional groundwater in the basin (Zhou et al. 2003). The Kaoping River is the largest river in the plain and is located near the western foothills with a length of 171 km and average slope of 1:43, flowing from north to south before reaching the sea.

Geology

The mountainous regions surrounding Pingtung Plain are composed of Tertiary age rock (Ting 1997). The rocks of the Suao Group of Eocene–Oligocene age are distributed on the east of the plain. They form a thick area of black slate intercalated with beds of coarse or fine-grained sandstone. The Chaochou fault, stretching from N–S, separates the Suao Group Formation and the Pingtung Plain. The Mucha Formation of Mio-Pliocene age is dominant in the region north of the plain. Its lower part, about 300 m thick, is composed mainly of sandstone and shale. The upper part of Mucha Formation is the Liukwei conglomerate with a thickness of 1,000 m. The conglomeration is a deposit of cobbles and boulders, mainly composed of hard sandstone of fist size. The Kutingkeng Formation of Pliocene Age is widely exposed on the northwest side of the Pingtung Plain. It consists mainly of sandy shale and beds of shale and sandstone. The Chiting Formation is also exposed northwest of the Pingtung Plain. This attains a thickness of 1,800 m; the lower 400 m is mainly shale and sandstone, while the upper 1,400 m comprises sandstone with some shale and sandy shale.

The unconsolidated sediments filling the Pingtung Plain are of Quaternary age and constitute the main aquifer in the plain (Ting 1997). The Pleistocene Lingkou conglomerate is a loose deposit about 300 m thick, outcropping as a narrow strip along the western edge of the hilly region in the north of the plain. It consists mainly of round pebbles and cobbles with dispersed sand and clay, and is occasionally intercalated with thin layers of sandstone. The older alluvium that consists of coarse material is distributed in the marginal

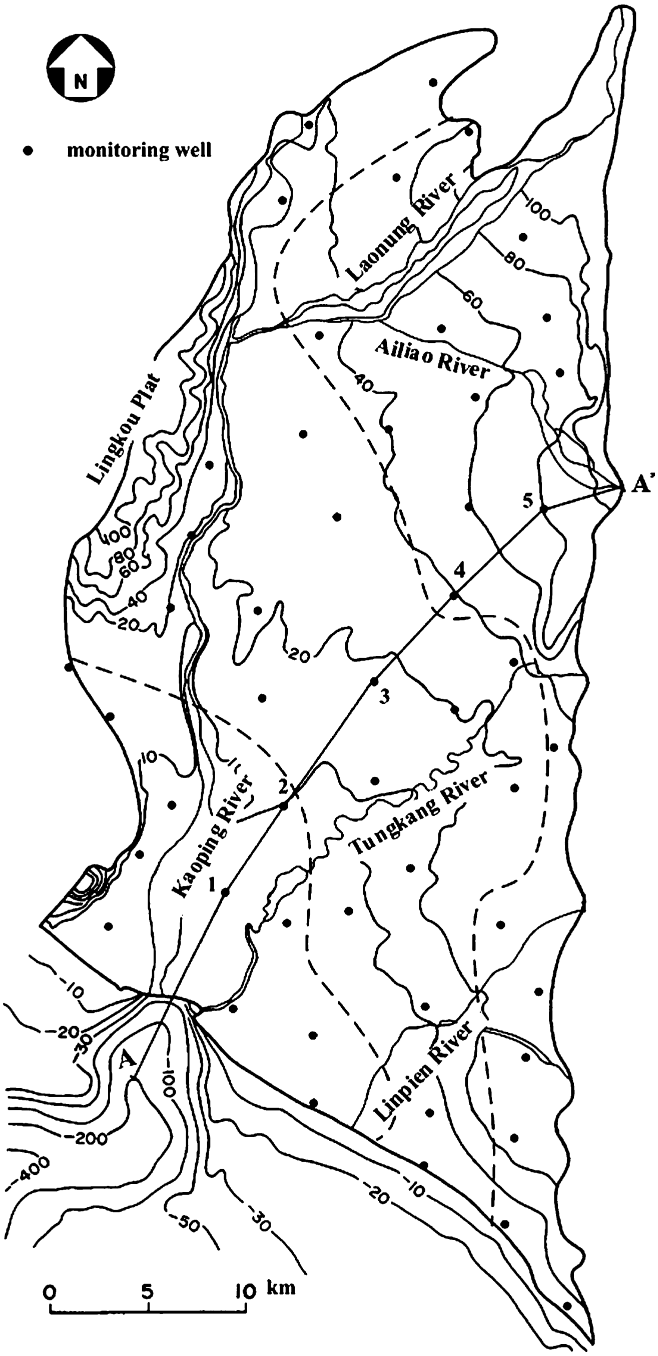

Fig. 3 Map of the Pingtung Plain. *Dashed lines* represent the boundaries of the alluvial fan (proximal, middle and distal regions); *black dots* are monitoring wells. Section *A–A'* and wells *1–5* are also shown in Fig. 4

zone of the Central Mountain Range. The recent alluvium filling the Pingtung Plain is the principal source of groundwater and consists of fan-like deposits and sediments from broad, braided river valleys. The maximum thickness of sediments of the recent alluvium is not yet known since the solid rock floor has not been reached by any deep wells and neither has the depth been determined by geophysical exploration. The recent alluvium may be divided into three zones with different materials: coarse gravel, alternating gravel, and sand and fine sediment.

Hydroclimatic conditions

The climate of the Pingtung Plain is sub-tropical. Average annual temperature is 24°C, with the highest monthly mean value in July (28°C) and the lowest in January (19°C). Rainfall is unevenly distributed in space. The long-term average precipitation ranges from 2,500 mm in the Tungkang catchment to 2,660 mm in the Kaoping catchment. The mean annual precipitation along the Kaoping River is about 3,000 mm and annual evaporation is 1,120 mm. The precipitation in the temporal domain is also uneven in that the ratio of precipitation in the dry season (October to April) to that in the wet season (May to September) is 1:9. During the wet season, typhoons and thunderstorms occur regularly producing most of the rainfall, while there is very little rain in the dry season. Evapotranspiration also varies seasonally. During the wet season, precipitation is higher than evapotranspiration and recharge to the aquifers can occur, while in the dry season, precipitation is less than evapotranspiration.

Water use

Because of the favorable climate, water supply, and soils, the Pingtung Plain is one of the most fertile agricultural regions in Taiwan. On average, only 20% of the surface water is utilized and consequently, groundwater is heavily relied upon in the Pingtung Plain. The groundwater supports the needs of agriculture, fish breeding, industry, and domestic drinking water in Kaohsiung and Pingtung counties. In the recent past, groundwater extraction is about 12 hundred million m^3/year in this area, which exceeds the estimated natural recharge of about 10 hundred million m^3/year (TPWCB 1998). The uncontrolled usage of the groundwater resource has led to undesirable impacts such as land subsidence, groundwater pollution, seawater intrusion, and reductions in well yields (TPWCB 1994). Analysis of these problems depends on sufficient and reliable information related to the hydrogeological structure of this region.

Methods

Groundwater data collection

The Bureau of Water Resources in Taiwan initiated a groundwater monitoring network project in 1992 to support long-term management of the groundwater resources. A network of 51 virtually evenly distributed stations had been established, including 127 monitoring wells drilled to depths ranging from 10 to 260 m. By 1997, all monitoring wells were completely installed and began to collect data on the aquifers. These monitoring wells provide groundwater-level data on an hourly basis. The monitoring network offers valuable information not only on the real-time groundwater variations, but also on the valuable hydrogeological and hydrochemical background including tritium and oxygen isotopes and electrical conductivity. Locations of the monitoring well stations are shown in Fig. 3.

Hydrogeological model

The Pingtung Plain is bounded by the high-angle Chaochou fault along its eastern side (Fig. 4; cross-section A–A') and comprises three aquifers (F1, F2, and F3) separated partially by three aquitards (T1, T2, and T3) based on the lithology data (CGS 2002). Aquifer 3 can be further divided into two sub-aquifers F3-1 and F3-2 based on their hydrofacies (Fig. 4). Gravel and sand mainly compose the aquifer while clay and silt make up the aquitard. The proximal part of the Pingtung Plain is mainly composed of gravel; aquifer layers cannot be distinguished in this region. The aquifer is very thick and the depth to the bedrock is not available from the existing drilling and geophysical data.

Pumping tests were performed in the Pingtung Plain to obtain hydrogeological parameters (CGS 2002). Totals of 127, 13, and 8 were indicated for hydraulic conductivity, specific storage, and specific yield, respectively. Most of the pumping tests were performed in aquifers and very little information is available for the aquitard due to the fact that the monitoring network was initially set up for the purpose of water supply.

Central Geological Survey (CGS) in Taiwan presented a hydrogeological model for the Pingtung Plain based on lithology, geophysical logging, stratigraphy, and pumping tests as shown in Fig. 4 (CGS 2002). Lithology data were obtained from geological drilling either using auger drilling in fine material or cable tool drilling in material with gravel. Geophysical data include electrical resistivity logging, natural gamma-ray logging, and spontaneous potential logging.

Recharge

Recharge is strongly related to precipitation and significantly affects the groundwater system. Site-specific recharge data are often not available or difficult to quantify. Therefore, recharge data are often used purely as fitting parameters during model calibration (Varni and Usunoff 1999). Where site-specific information about precipitation is available, an assumed fraction of it is commonly assigned as the recharge boundary condition (Brodie 1999; Kennett-Smith et al. 1996). Such assumptions may be adequate for the long-term simulation of the regional groundwater flow system (Jyrkama et al. 2002) as was done here.

Methods of water-table fluctuation (Healy and Cook 2002) and model inversion were combined to estimate the recharge in this study. The water-table fluctuation method was used first to identify characteristics of the relationship between precipitation and recharge. Then the regional recharge was determined through model calibration, and the relation between recharge and precipitation was applied for the use of evaluating the impact of climate changes on the groundwater system.

Since the coarse material lies on most of the top area of the Pingtung Plain and the groundwater level is shallow in this region (Fig. 4), fast responses of the groundwater level to rainfall events are expected. Three water-level time series (1997–2005) of shallow aquifers of wells 1, 3, and 4 located in the distal, middle, and proximal fan, respectively (well locations can be found in Figs. 3 and 4 along cross-section A–A'), were analyzed by the water-table fluctuation method using the high end of the values of specific yield (0.10) obtained from pumping tests in the Pingtung Plain to estimate their recharges. Well 5, which is located in the proximal fan but close to the inlet of Ailiao stream, was also analyzed (data period of 1998–2005) to evaluate the effect of lateral recharge. Table 1 shows the regression results of the precipitation and recharge. The results indicate that recharges of all wells are well represented by linear functions of the precipitation. Regression coefficients (slopes of the regression equation) indicate that recharge decreases from the proximal fan to the distal fan and the difference will be greater if soil material (different specific yields) is considered. Including lateral recharge, the recharge of well 5 can be also represented by a linear relationship to precipitation (Table 1). This indicates that the lateral recharge may be linked to precipitation by a linear relationship, which may be explained by the fact that the surrounding mountainous formations are nearly impermeable and with poor water-bearing properties; runoff and infiltration are the main mechanism for groundwater supply from lateral boundaries. The results of the water-table fluctuation method indicate that both plane recharge and lateral recharge may be related to precipitation by linear functions. The characteristic of the linear relation between the recharge and the precipitation may be improved at a more complicated form when more data are available. The linear relationship is utilized in this study in modeling the long-term response of the groundwater system to climate changes.

Numerical model

The finite-difference numerical software MODFLOW SURFACT (Hydrogeologic 1996) was used to investigate the impacts of climate changes on the groundwater system of the Pingtung Plain. The modeling domain was subdivided into uniform rectangular grids of 72 rows and 32 columns (Fig. 5). Cell size was set at 1,000 m by 1,000 m. Seven layers representing four aquifers (F1, F2, F3-1, and F3-2) and three aquitards (T1, T2, and T3) in the hydrogeological model (Fig. 4) were considered. Plane recharge was applied to the top layer and varied spatially (Fig. 5). Different recharge rates were assigned monthly for recharge zones and for the wet and dry seasons based on the annual precipitation. The final recharge rates were determined through model calibration. Lateral recharges were simulated through different layers by variable flux Neumann boundary conditions. The values varied propor-

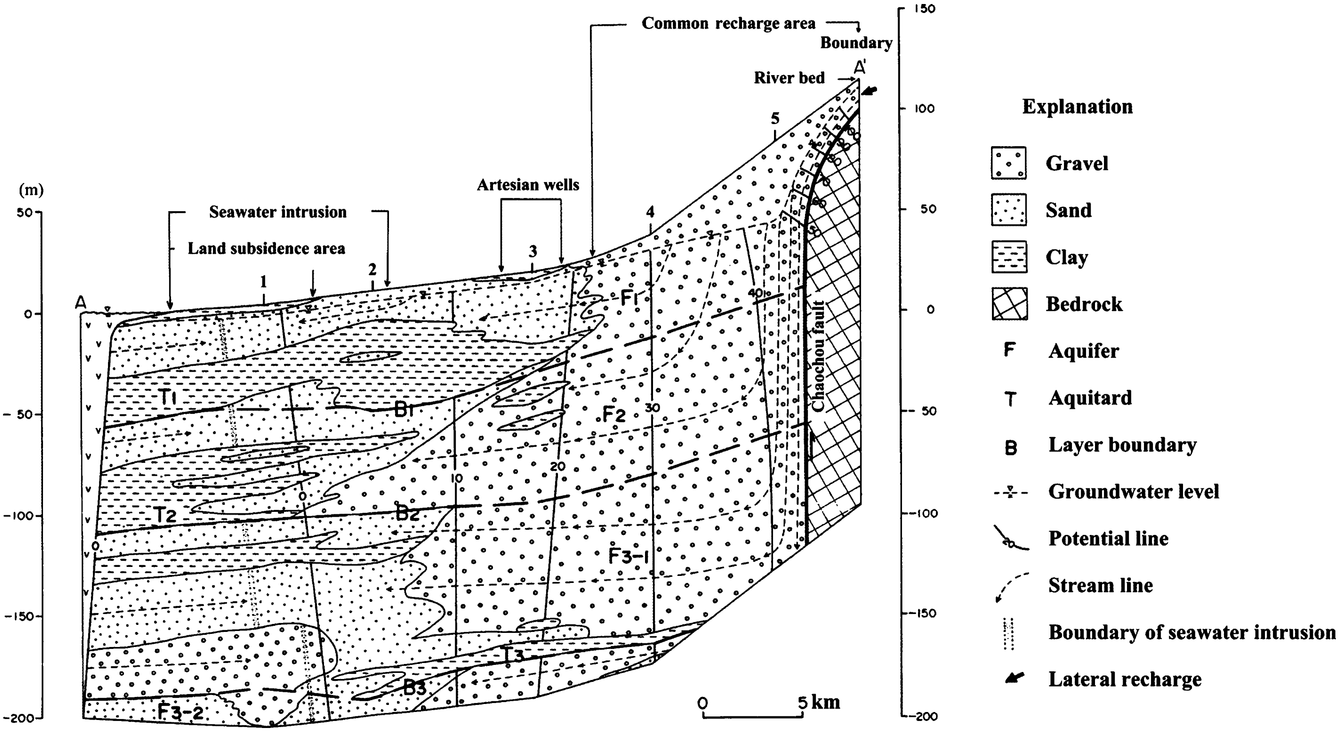

Fig. 4 Hydrogeological model of the Pingtung Plain in this study. 1–5 refers to the five wells

tionally with the amount of annual total precipitation. Instead of implementing the river package, stream recharge was combined into the plane recharge due to the lack of stream-water-level data and the fact that streams usually remain in a low-flow situation except during the storm periods (WRA 2004). Neumann boundary conditions were assigned to nine cells to represent the inlets of Kaoping, Tungkang, and Linpien rivers from the mountain area to the plain (Fig. 5). No flow boundaries were assigned to the northern, eastern, and western boundaries because of poor permeability and water-bearing properties of the formation surrounding the plain. The bottom of the domain was assigned as a no flow boundary desspite the fact that the depth of the aquifer is not yet known. A constant-head Dirichlet boundary condition is assigned to the southern boundary to represent the ocean. The uncertainty in the Pingtung Plain modeling may also involve estimating the amount of extracted groundwater for various usages. The preliminary investigation on amounts of extracted groundwater in each village was performed by TPWCB (1998). The extraction of groundwater was modeled by using the fracture well package of MODFLOW SURFACT to avoid the modeling problem of active cells transforming to inactive cells due to sequentially dry–wet interactions. The amount of extraction was adjusted based on the calibration results.

Table 1 Regression formula of recharge and precipitation in the Pingtung Plain

Well	Location	Data period	Regression formula *X*: precipitation (mm), *Y*: recharge (mm)	Correlation coefficient
1	Distal fan	1997–2005	$Y = 0.17X + 10.42$	0.94
3	Middle fan	1997–2005	$Y = 0.19X + 342.46$	0.91
4	Proximal fan	1997–2005	$Y = 0.29X + 152.02$	0.93
5	Proximal fan	1998–2005	$Y = 0.55X - 357.47$	0.87

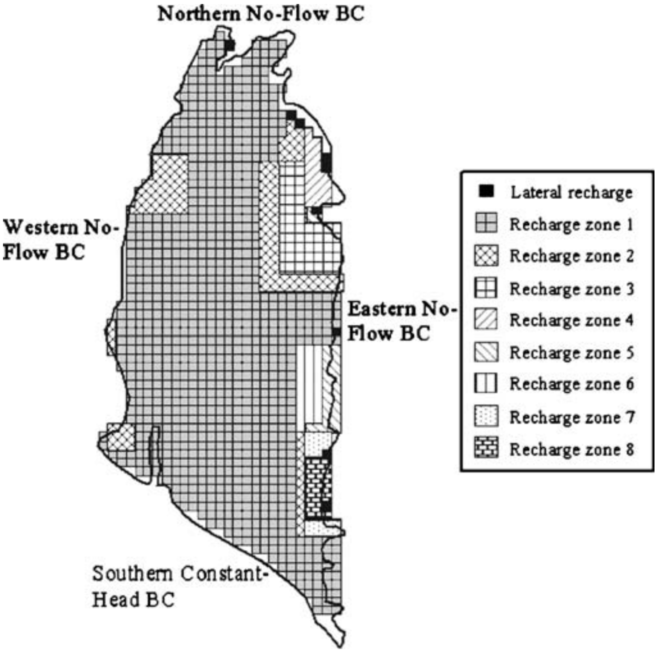

Fig. 5 Numerical finite-difference model of the Pingtung Plain showing model grid, model boundary types, and recharge zones

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Two steps were adopted to construct the spatial distribution of hydraulic conductivity of the numerical model. First, indicator kriging (Deutsch and Journel 1998) was performed to delineate the spatial distribution of aquifers and aquitards based on the lithology information. Then, the result was refined based on the constructed hydrogeological model. Second, with 127 field hydraulic conductivities and standard textbook values for the aquitards (Freeze and Cherry 1979), ordinary kriging was performed to assign the hydraulic conductivity in the layer system. The values of hydraulic conductivity in the aquifers range from 10^{-3} to 10^{-5} m/s. The values of specific storage and specific yield range from 10^{-5} to 10^{-6} and from 10^{-1} to 10^{-3} l/m, respectively. The hydraulic conductivity of clay was assigned to the aquitard (10^{-6} to 10^{-7} m/s). Kriging results are used as the initial spatial distribution of the hydraulic conductivity field for model calibration.

Model calibration and verification

Model calibration was achieved through the classic trial-and-error procedure, by matching simulated heads with observed heads. A total of 6 years (1997–2002) of groundwater-level data are available for the Pingtung Plain modeling. The first 5 years of data were used to calibrate the model. Before the transient simulation, data from year 1997 were used five times consecutively to eliminate the effect of initial conditions on modeling. The average error (calculated water level–observed water level) of dry and wet seasons is 0.03 m and the root mean square error (RMSE) is 2.49 m for years 1997–2002. The data of year 2002 was used to validate the model. The average error of dry and wet seasons is −0.7 m and the modeling RMSE is 2.76 m. The calibration results are acceptable since the observed average annual groundwater level fluctuation is 10 m and can be up to above 20 m in the proximal fan. The model can be improved if detailed transient recharge or evapotranspiration data are available.

Hydrological impacts of climate change on water-resource management of the Pingtung Plain

Previous analyses on precipitation data of Taiwan showed two possible impacts on precipitation in southwest Taiwan. First, the amount of annual precipitation decreases 7.84 mm/year. Second, the annual precipitation days decrease 0.57 days/year. Applying the linear regression results of the amount of annual precipitation and precipitation days to the next 20 years (2003–2022), the precipitation will gradually decrease from 2,141.2 mm (the average annual precipitation of modeling period 1997–2002) to 1,984.2 mm in 2023, and the precipitation days will decrease 11.4 days in 2022 compared to the present time. In this study, the effect of climate change on the groundwater system is assumed to reflect the amount of annual precipitation. The precipitation is directly linked

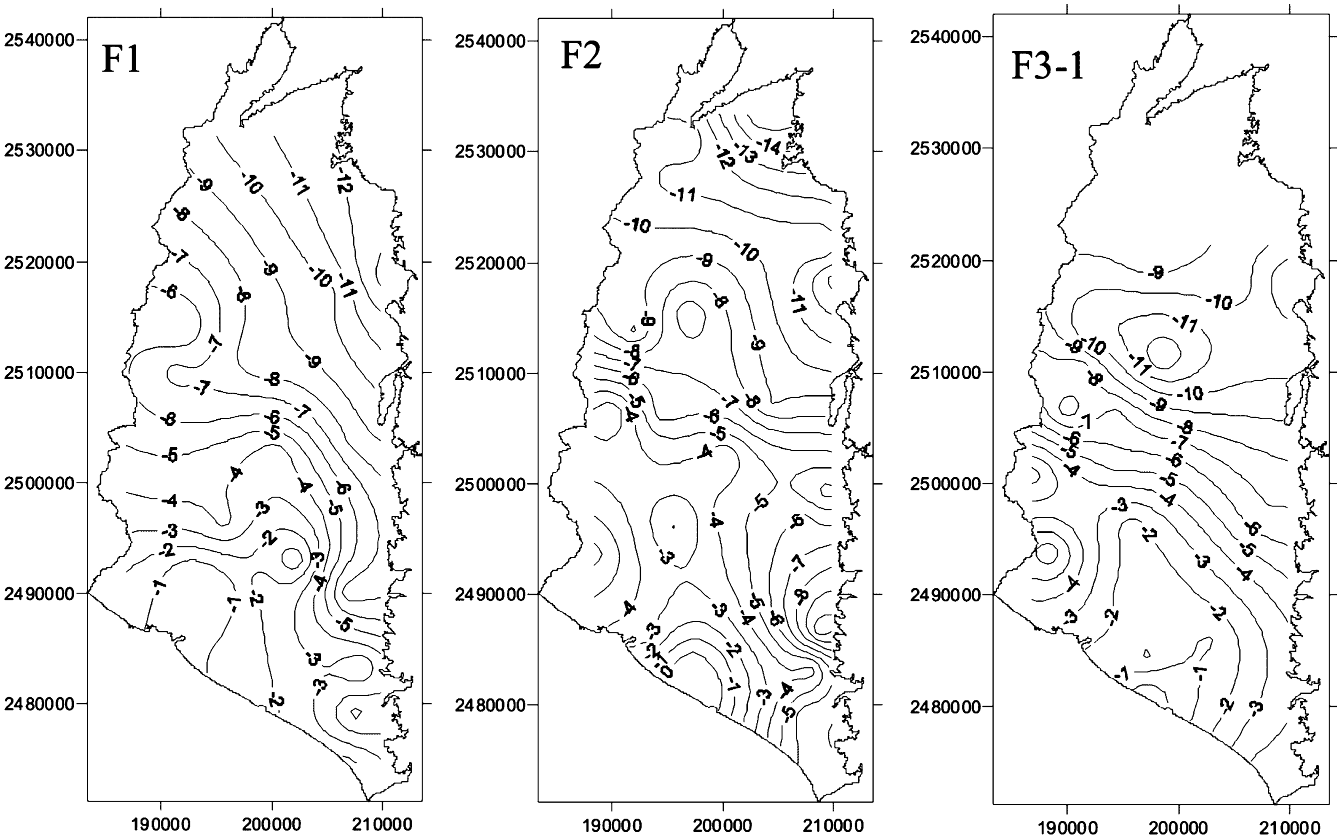

Fig. 6 Contour maps of groundwater level differences (2002 water levels minus 2022 levels) in meters for the wet season (September) for aquifers *F1*, *F2,* and *F3-1*

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to the recharge by linear relationships based on the analysis of recharge and model calibration.

To explore possible impacts of climate change on the Pingtung Plain in the next two decades, the annual precipitation rate reduction of 7.84 mm/year and its reflection in the reduction of recharge were applied to the modeling. Except for the recharge, the modeling parameters remained the same as in the model calibration and verification. Although groundwater extraction may play an important role in the response of a groundwater system to the climate changes, its effect was not included in modeling because first, the population in this region shows a negative growth rate (−0.15% based on population data 1996–2005) due to population migration and, second, the water demand in the Pingtung Plain is dominated by the needs of agriculture, fish breeding and industry but not domestic use. The amount of groundwater extraction in the modeling was therefore assumed to remain the same.

Figures 6 and 7 illustrate the results for the main aquifers (F1, F2, and F3-1) with contour maps of groundwater level differences between 2002 and 2022 for wet and dry seasons, respectively. Applying long-term declining annual precipitation to the groundwater system for the following 20 years has the result of significantly decreasing groundwater level. Figure 6 shows that under the impact of climate change, groundwater levels in the wet season of 2022 will be more than 3 m lower than those at present time in the proximal fan. In the northern part of the Pingtung Plain the groundwater difference can be up to 10 m. In the coastal area, the groundwater level decreases ranging from 0 to 6 m. Figure 7 shows the result for the dry season. The situation in the dry season seems worse than that predicted in the wet season. The groundwater level considering climate impact is significantly lower than that in 2002. The water-level difference significantly increases from the coastal area to the inland area. The difference of groundwater levels in the dry season was about one to two m more than those in the wet season in the proximal fan. Half to two-thirds of the whole plain produces a groundwater level difference of more than 5 m compared to the present time. Such a difference indicates a decrease of hydraulic gradient and a reduction of groundwater flow rate in the Pingtung Plain in the future.

Since the proximal fan is the most important region for water to recharge the groundwater system, the lowering groundwater level in this area over time may raise an alarm concerning the decrease of available groundwater under the stress of climate change. The results also suggest that the groundwater level in the distal fan will tend to decline in the future. Therefore, the stress of climate change would cause a more serious water-level decline. While the distal fan is the major area for seawater intrusion and land subsidence in the Pingtung Plain, the enlargement of area with a groundwater level below sea

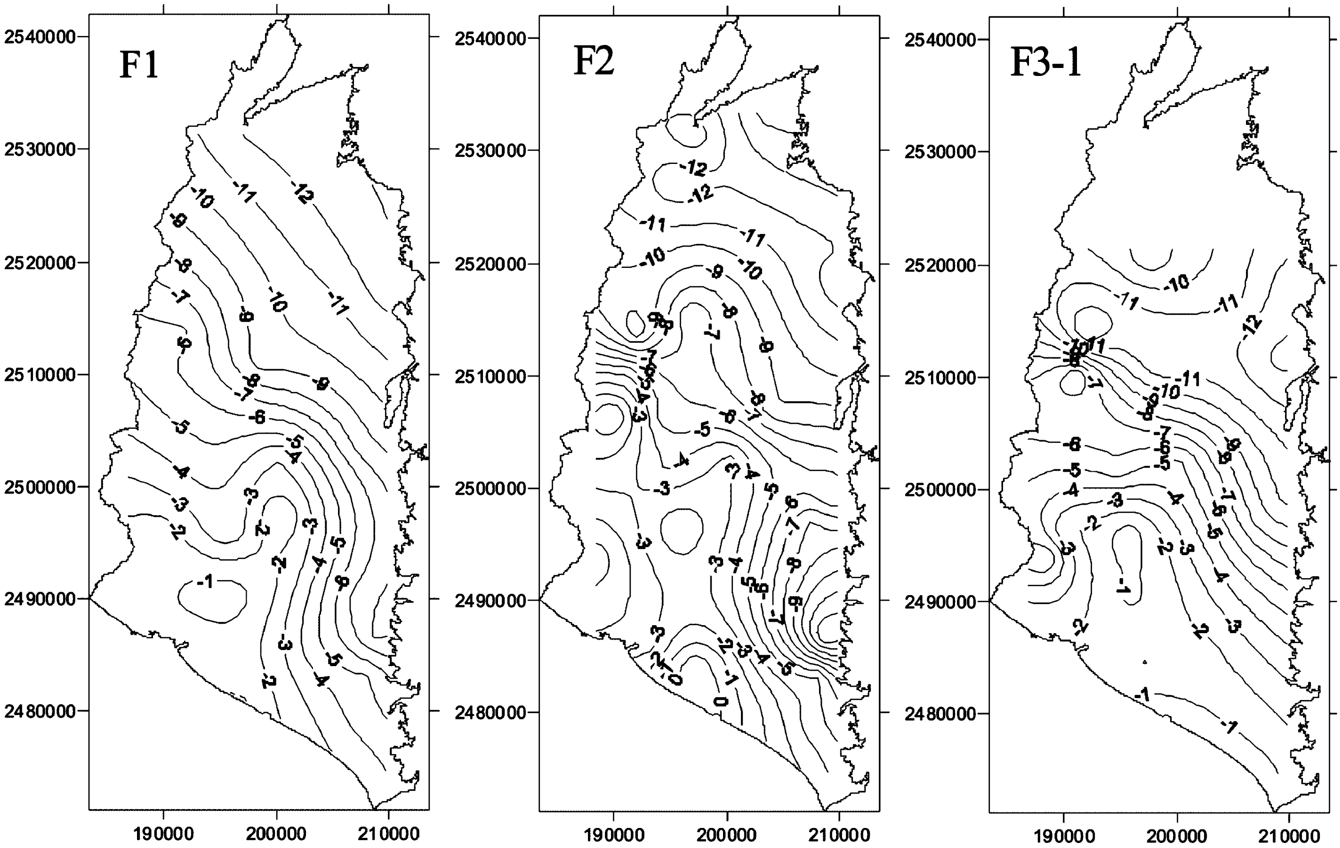

Fig. 7 Contour maps of groundwater level differences (2002 water levels minus 2022 levels) in meters for the dry season (March) for aquifers *F1*, *F2*, and *F3-1*

level heralds a warning for the possible deterioration of the groundwater-resource situation in the future due to climate change. The climate change may lead to the destruction and degradation of water ecosystems and aquifers. The existing facilities and management system of water resources of the Pingtung Plain may not be reliable under the stress of climate change. Measures such as detention of surface waters, artificial recharge, regulation of extraction of groundwater, implementation of water conservation and minimizing deterioration of the quality of available water may help to prevent the deterioration of the water resources in the Pingtung Plain that may happen due to climate change.

Assumptions/limitations

As with any hydrologic model, the modeling results are subject to a number of assumptions and approximations. The model calibration may be improved by using small-scale transient recharge knowledge. Also, the linear regression of precipitation used in this study can only provide the possible trend of future climate changes due to the inconclusive precipitation prediction of Taiwan in previous research (Hsu and Chen 2002). This may be feasible for the conservative purpose of water-resource management. Risk and uncertainty assessments of groundwater resources will require stochastic analysis such as Monte Carlo simulations. Although any firm statements regarding the accuracy of the modeling results cannot be made without further verification and evaluation, the developed methodology nevertheless provides a practical and useful way to generate a physically based evaluation of the impacts of climate change on a groundwater system.

Summary and conclusions

Regional hydrological impacts due to climatic variation on the groundwater system of the Pingtung Plain, Taiwan, were modeled and the results discussed herein. Records of more than 60 years of precipitation data were analyzed to find the long-term patterns of climate change. The characteristics of precipitation change in Taiwan are inhomogeneous in space and, also, non-stationary in time. Particularly in southwestern Taiwan, both the amount and days of annual precipitation tend to decrease. Such a change in the precipitation pattern indicates that climate change may induce instability of surface-water resources in the future, thus increasing reliance on groundwater resources. Linear regression analyses were performed using the historical precipitation data and were used to predict the possible situation in the next 20 years.

The Pingtung Plain, one of the most important aquifers of southwestern Taiwan, was utilized to model the impact of climate change. A numerical model was built based on the hydrogeological model, which comprises information on lithology, hydraulic conductivity, electrical conductivity, and tritium and oxygen isotopes.

Applying the linear regression relationship of precipitation to the next 20 years, the outputs of numerical modeling show that under the stress of climate change, the groundwater level in the proximal fan of the Pingtung Plain will decrease most seriously. While the proximal fan is the most important region for groundwater recharge, the lowering water level in this area raises an alarm regarding the decrease of available groundwater in the future. Modeling results also show that areas of water level below sea level will expand in the distal fan, because the distal fan is the major area of seawater intrusion and subsidence in the Pingtung Plain. The enlargement of the area with a groundwater level below zero elevation should present a serious warning for the deterioration of groundwater resources in the future. The trends of decreasing the amount of precipitation and increasing the precipitation intensity in the future would generate more difficulties in utilizing both surface and groundwater resources. Even if the impact of climate change on the groundwater system is slower compared to the surface water, the groundwater system may not sustain the water demand under the stress of climate change in the Pingtung Plain in the future. The existing facilities and management system of water resources may not be reliable under the stress of climate change. Suitable strategies for water-resource management in response to hydrological impacts of future climatic change are imperative.

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