Plan for a groundwater monitoring network in Taiwan

Shiang-Kueen Hsu

Abstract In Taiwan, rapid economic growth, rising standards of living, and an altered societal structure have in recent years put severe demands on water supplies. Because of its stable quantity and quality, groundwater has long been a reliable source of water for domestic, agricultural, and industrial users, but the establishment of a management program that integrates groundwater and surface-water use has been hampered by the lack of groundwater data. In 1992, the Department of Water Resources (DWR) initiated a program entitled "Groundwater Monitoring Network Plan in Taiwan." Under this program, basic groundwater data, including water-level and water-quality data, are being collected, and a reliable database is being established for the purpose of managing total water resources. This paper introduces the goals, implementation stages, and scope of that plan. The plan calls for constructing 517 hydrogeologic survey stations and 990 groundwater monitoring wells within 17 years. Under this program, water-level fluctuations are continuously monitored, whereas water-quality samples are taken for analysis only at the initial drilling stage and, subsequently, at the time when a monitoring well is being serviced. In 1996, the DWR and the Water Resources Planning Commission were merged to form today's Water Resources Bureau.

Résumé A Taïwan, l'expansion économique rapide, l'amélioration des conditions de vie et la transformation de la structure sociale ont provoqué, ces dernières années, une très forte demande en eau. Du fait de sa constance en qualité et en quantité, l'eau souterraine a longtemps été considérée comme une ressource en eau sûre pour les usages domestiques, agricoles et industriels. Mais la mise en place d'un programme de gestion intégrant les utilisations d'eaux souterraines et de surface a été gênée par l'absence de données sur les eaux souterraines. En 1992, le Département des Ressources en Eau a lancé le programme "Plan pour un réseau de suivi des eaux souterraines à Taïwan". D'après ce programme, les données de base concernant les eaux souterraines, comprenant les mesures de niveau et les données de qualité, ont été acquises ; une base de données sûre est en cours d'élaboration, dans le but de gérer l'ensemble des ressources en eau. Cet article présente les buts, les stades de développement et une vue d'ensemble de ce plan. Le plan impose la mise en place de 517 stations de mesures hydrogéologiques et de 990 piézomètres en 17 ans. Selon ce programme, les variations du niveau des nappes doivent être suivies en continu, tandis que des échantillons pour la qualité de l'eau seront prélevés pour analyses uniquement au cours de la phase de foration, puis au moment de la mise en service des piézomètres. En 1996, le Département des Ressources en Eau et la Commission de Planification des Ressources en Eau ont été réunis pour former l'actuel Bureau des Ressources en Eau.

Resumen En Taiwan, el rápido crecimiento económico, el aumento en el nivel de vida y los cambios sociales en los últimos años han resultado en un aumento en la demanda de agua. Por su estabilidad en términos de cantidad y calidad, las aguas subterráneas han sido durante años la fuente de agua para usos domésticos, agrícolas e industriales. En los últimos años, sin embargo, el establecimiento de un programa de gestión conjunta de aguas superficiales y subterráneas se ha visto comprometido por la falta de datos correspondientes a estas últimas. En 1992, el Departamento de Recursos de Agua (DWR) inició un programa titulado "Plan de Red de Control de Aguas Subterráneas en Taiwan". Bajo este programa, se están recogiendo datos básicos, incluyendo niveles piezométricos y datos de calidad, y se está construyendo una base de datos con el propósito de gestionar los recursos de agua totales. Este artículo presenta el marco, los objetivos y el estado de implantación del plan, que pretende la construcción de 517 estaciones de medida hidrogeológicas y 990 pozos de observación durante un periodo de 17 años. Bajo este programa, los niveles de agua se miden continuamente, mientras que las muestras para análisis de calidad se toman sólo durante la perforación y cuando el pozo está en servicio. En 1996, el DWR y la Comisión

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de Planificación de los Recursos de Agua se unieron para formar la actual Oficina de Recursos de Agua.5

Key words Taiwan · groundwater monitoring · organizations · subsidence · network plan

Introduction

Taiwan, an island in the Pacific Ocean, is about 300 km long from north–south and about 120 km wide from west–east. As shown in *Figure 1*, Taiwan is separated from mainland China by the Taiwan Strait and is located in the tropical and subtropical regions; the Tropic of Cancer passes through the city of Chia-Yi in southern Taiwan.

Steep mountain terrain above 1000 m in elevation occupies about 32% of the central area of Taiwan. Hills and terrace land between 100–1000 m occupy another 31%. Thus, almost two-thirds of the island consists of steep terrain. The annual precipitation of Taiwan ranges from 4000–5000 mm in mountain areas, and 1500–2000 mm in the plain and coastal areas. However, almost all rivers in Taiwan flow west from the central mountain area into the Taiwan Strait and are short and steep; during the storm period, river discharge becomes torrential. About 78% of the annual precipitation takes place during the wet season (from May to October), when a major portion of the precipitation is generated by typhoons and thunderstorms. Runoff is estimated to be 100 billion m^3 during the wet season, but only 40 billion m^3 during the dry season, from November to April (WRPC 1989). Thus, the temporal and spatial distributions of precipitation are extremely uneven, making careful management of water resources in Taiwan crucial.

Because of the unusual geographic and hydrologic conditions of Taiwan, described above, surface-water resources are limited. In 1959, the government began construction of a series of reservoirs and, to date, 35 major reservoirs have been completed. The current effective storage capacity of all reservoirs is about 2.3 billion m^3, and the operational volume is about 4 billion m^3 (DWR 1996b). But the expansion of aquaculture and industry to accommodate the rapid population growth of the past three decades has increased water demand from 10 billion m^3 in 1961, to 15 billion m^3 in 1971, to 18 billion m^3 in 1992 (Wu 1994). A water demand of 21 billion m^3 is expected for the year 2010, if the projected agricultural, industrial, and domestic requirements are realized.

Concurrently, as the demand for water supplies has risen, the lower costs, the accessibility, and the more stable quality of groundwater have encouraged groundwater pumping. Exploration for groundwater, ongoing since 1885, has been confined to shallow aquifers. But with the introduction of modern drilling techniques by the US Johnson International Corporation in 1950, the Taiwan Sugar Corporation was able to explore a total area of 4100 km^2. Their explorations indicate that many locations of Taiwan are underlain by unconsolidated rocks, commonly composed of sand and gravel – formations that commonly are water bearing.

The annual groundwater withdrawal in Taiwan is estimated to be 3.2 billion m^3 in 1975, 4.1 billion m^3 in 1983, 6.3 billion m^3 in 1988, and 7.1 billion m^3 in 1991 (Wu 1992). The annual groundwater recharge, however, is estimated to be only 4 billion m^3. Over-pumping of groundwater by various water users, such as the recently and extensively developed aquaculture industry in the coastal area, has lowered the water table in this area. Consequently, the water level is declining every

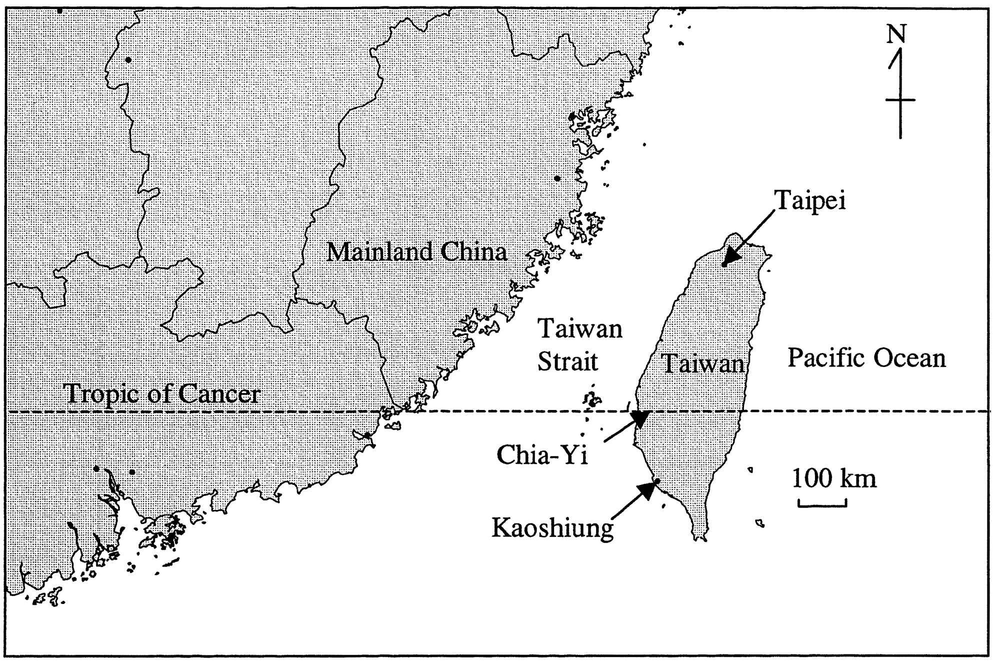


Fig. 1 Location of Taiwan

year. The resulting consolidation of land strata triggers land subsidence. More than 100,000 illegal wells are operating in the coastal area.

The primary threats to groundwater quality are from the following sources: (1) infiltration of polluted surface water to shallow unconfined aquifers; (2) seepage from polluted streams that are hydraulically connected to groundwater; (3) salt-water intrusion in the coastal area, due to over-pumping; and (4) illegal injection of industrial wastes into deep aquifers. The Environmental Protection Agency (EPA) of Taiwan is responsible for the detection and protection of groundwater contamination. The Water Resources Bureau (WRB) is responsible for stopping the illegal pumping and for the issuing of permits for well drilling, in accordance with the Water Resources Law established in Taiwan. However, the lack of reliable groundwater data makes it difficult to quantify and control the groundwater resources as well as land subsidence.

Review of Groundwater Monitoring in Taiwan

As described above, development of groundwater resources is vital to the water supply in Taiwan. Of the total amount of water consumed in Taiwan, groundwater accounted for about 21.5% in 1983 and 40.3% in 1991 (WRPC 1996). As early as 1959, the Taiwan Provincial Government recognized the need for developing groundwater resources island-wide. At that time, with the establishment of the Groundwater Engineering Division, nine groundwater basins with a total area of 10,330 km^2 were identified and explored. These groundwater basins, as shown in *Figure 2*, include the Taipei basin, Taoyuan–Chungli terrace, Hsinchu–Miaoli coastal area, Taichung area, Choshui River alluvial fan, Chianan plain, Pingtung plain, Lanyang plain, and the Hualien–Taitung valley (Hengchun plain and Penghu Island were included in this plan). The basin boundaries were determined from the available geological and hydrogeological information, as well as by institutional constraints. In 1959, the Groundwater Engineering Division also began construction of a groundwater monitoring system of 300 observation wells, which were completed in 1966. *Table 1* shows the chronological development of groundwater monitoring in Taiwan.

In 1966, the Groundwater Engineering Division was reorganized into a subdivision of the Taiwan Provincial Water Conservancy Bureau. From 1966 until 1976, the

Fig. 2 Groundwater flow regimes and implementation schedule of the Groundwater Monitoring Network Plan in Taiwan. (After DWR 1996a)

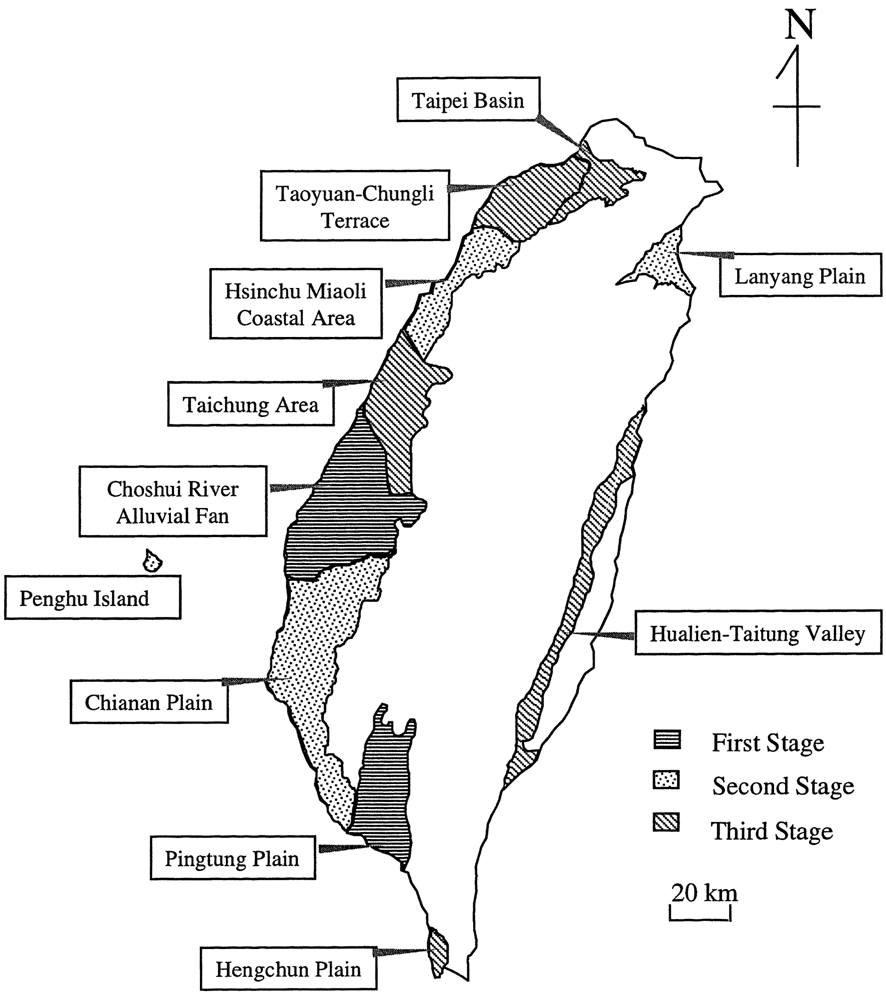


Table 1 Overview of the development of the groundwater monitoring network

Year	Activity	Responsible agency
1959	Groundwater Engineering Division formed. A monitoring system consisting of 300 observation wells initiated and completed in 1966	• Groundwater Engineering Division, Taiwan Provincial Government
1966	Mission of Groundwater Engineering Division accomplished. The monitoring system expanded to 339 wells in 1987	• Groundwater Engineering Division, Taiwan Provincial Water Conservancy Bureau, Taiwan Provincial Government
1976	Groundwater Engineering Division abolished. The responsibilities of maintaining the monitoring system switched to another agency	• Hydrologic Survey Team, Taiwan Provincial Water Conservancy Bureau, Taiwan Provincial Government
1986	Representative from USGS[a] visited Taiwan and suggested that a new groundwater monitoring network was needed	• Council for Economic Planning and Development • Council of Agriculture
1987	Planning of groundwater monitoring network started and completed in 1992	• Council of Agriculture • Taiwan Provincial Water Conservancy Bureau, Taiwan Provincial Government
1991	Installation of groundwater monitoring network started	• Department of Water Resources, MOEA[b]
1992	A master plan entitled "Groundwater Monitoring Network Plan in Taiwan" formed, based upon the planning results	• Department of Water Resources, MOEA[b] • Council for Economic Planning and Development
1996	The "Groundwater Monitoring Network Plan in Taiwan" fully authorized	• Executive Yuan

[a] USGS, United States Geological Survey
[b] MOEA, Ministry of Economic Affairs

Groundwater Engineering Division of the Taiwan Provincial Water Conservancy Bureau was responsible for managing the groundwater monitoring project, and the monitoring system was expanded. With the abolition of the Engineering Division in 1977, the Hydrologic Survey Team of the Taiwan Provincial Water Conservancy Bureau was put in charge of the groundwater monitoring system. By 1987, the monitoring system consisted of 339 observation wells, 37 of which had automatic data-logging devices.

In 1986, the US Geological Survey (USGS) was invited by the Council for Economic Planning and Development and the Council of Agriculture to visit Taiwan and to review its installed groundwater monitoring system (TPWCB 1988–1992). Because the system could not gather data on land subsidence, the USGS recommended that a new groundwater monitoring system be established. The new system would be designed to collect data adequate to support the long-term planning and management of groundwater resources.

In 1987, the Council of Agriculture of the Executive Yuan funded the Taiwan Provincial Water Conservancy Bureau (TPWCB) to conduct a planning project on "Improving the Groundwater Hydrological Data Collection System in Taiwan" (TPWCB 1988–1992). In 1992, the Department of Water Resources (DWR) was requested to set up a plan entitled "Groundwater Monitoring Network Plan in Taiwan," which is described in detail in DWR (1996a) and Hsu et al. (1996). Since then, the DWR has taken the responsibility for planning, supervising, and raising funds for the plan. The Central Geological Survey and the Taiwan Provincial Water Conservancy Bureau, along with other related agencies, were called upon to establish a task force to implement the plan. The overriding objective of the plan is to collect data at the regional scale that ultimately would be used for groundwater-resources planning and management.

Goals

The direct and indirect goals of the plan are to be accomplished in three phases (DWR 1996a).

The direct goals of this plan are to do the following:

1. Establish a groundwater-monitoring network in Taiwan that would provide long-term hydrogeologic and hydrologic information and groundwater-quality data; install an automated water-level recording device at each monitoring well; and collect water-level and water-quality data and immediately process and electronically store the collected data.
2. Conduct research on groundwater hydrology and hydrogeology; characterize each groundwater flow regime; and identify the hydrogeologic system of each groundwater flow regime.
3. Establish a groundwater database and a comprehensive information system, including a decision-making system, and allow groundwater data to be conveniently shared among interested parties.
4. Recommend regulations for using and conserving groundwater resources.

The indirect goals of this plan are to do the following:

1. Provide information for management and conservation of groundwater resources.
2. Provide a baseline for the control of groundwater over-pumping and the mitigation of land subsidence.
3. Provide information necessary for conjunctive-use planning and management of local surface water and groundwater.

Phase I (Stage I) covers from 1992–98, and within that period, the following short-term goals are to be accomplished:

1. Complete a groundwater-monitoring network and a hydrogeological survey of the Choshui River alluvial fan, the northern part of Chianan plain, and Pingtung plain, where land-subsidence problems have been most serious.
2. Complete hydrogeological fence diagrams, identify aquifer parameters, establish groundwater-level contours, and evaluate aquifer storage for the areas stated above.
3. Establish a groundwater information system for the areas stated above.
4. Establish regulations for management and conservation of groundwater resources.

During Phase II (Stage II), from 1999–2003, the following intermediate goals are to be accomplished:

1. Complete a groundwater monitoring network and hydrogeological survey of the southern part of Chianan plain, Hsinchu-Miaoli coastal area, Lanyang plain, and Penghu Island.
2. Complete hydrogeological fence diagrams, identify aquifer parameters, construct groundwater-level maps, and evaluate aquifer storage for the areas stated above.
3. Establish regulations for groundwater-resources management and conservation.
4. Integrate a groundwater information system for all areas targeted during 1992–2003.
5. Establish a groundwater-quality database for all areas targeted during 1992–2003.

In Phase III (Stage III), 2004–08, the long-term goals to be accomplished include the following:

1. Complete a groundwater-monitoring network and hydrogeological survey at the Taipei basin, the Taoyuan-Chungli terrace, the Taichung area, the Hualien–Taitung valley, and the Hengchun plain.
2. Complete hydrogeological fence diagrams, identify aquifer parameters, construct groundwater-level maps, and evaluate aquifer storage for the areas stated above.
3. Establish regulations for the management and conservation of groundwater resources.
4. Integrate a groundwater information system throughout Taiwan.
5. Establish a groundwater-quality database throughout Taiwan.
6. Establish a groundwater database and integrated information system, including a decision-making system.

Guidelines

Based upon the well-log data from 2535 wells islandwide, the guidelines for the planning and implementation of the Groundwater Monitoring Network Plan in Taiwan include the following (DWR 1996a):

1. Identify groundwater flow regimes and boundaries from the groundwater flow pattern, and install groundwater monitoring wells evenly distributed in each flow domain.
2. Install groundwater monitoring wells at a density of about 20 km^2/station, with additional wells to be installed in areas of over-pumping and land subsidence. The density of 20 km^2/station was decided by a panel of experts using prior hydrogeological information. The installation of wells is to be done in stages. Information gathered at previous stage(s) is to be used to design the new well locations for the current stage. Kriging and Kalman filtering are to be used to optimally select the new well locations.
3. Install groundwater monitoring wells, followed by an analysis of the geologic framework of the groundwater flow regime.
4. Install nested monitoring wells for layered aquifers.
5. After completion of one-half to two-thirds of the planned groundwater monitoring wells, review the network to allow evaluation of plans for installing wells in the future.

Scope

The Groundwater Monitoring Network Plan in Taiwan covers the nine groundwater basins mentioned earlier as well as the Penghu Island and Hengchun plain areas, as shown in *Figure 2*. The original 1990 plan, described by TPWCB (1988–92) recommended the establishment of 577 hydrologic survey stations and 1071 groundwater monitoring wells. *Table 2* shows the numbers of stations and wells per groundwater basin. Construction began in 1991. Based upon the data collected and experience gained, the plan was modified in 1995. The final plan calls for 517 hydrologic survey stations and 990 groundwater monitoring wells. *Table 3* shows the number of stations and wells per stage per groundwater basin. Because of financial constraints, this plan is to be accomplished in three phases over a period of 17 years. The total estimated implementation cost was 6.4 billion NT$, and is itemized in *Table 4*.

The current plan aims at developing a reliable groundwater monitoring network in Taiwan to collect long-term groundwater data. Arrangements have been made for collaboration between the Water Resources Bureau, the Central Geological Survey, Taiwan Provincial Water Conservancy Bureau, the Energy and Resource Laboratories of the Industrial Technology Research Institute, and the Groundwater Development and Conservancy Center of the Taiwan Sugar Corporation.

The scope of the current plan (DWR 1996a) includes the following six work items: (1) conduct hydro-

Table 2 Planned hydrogeologic survey stations and groundwater monitoring wells. (After TPWCB 1988–92)

Groundwater basin		Groundwater monitoring stations		Number of groundwater monitoring wells
Name	Area (km^2)	Number	Density (km^2/station)	
Choshui River alluvial fan	1800	85	21.2	181
Pingtung plain	1130	60	18.8	128
North part of Chianan plain	300	15	20.0	32
South part of Chianan plain	2200	111	20.0	236
Hsinchu–Miaoli coastal area	900	53	17.0	94
Taipei basin	380	30	12.6	51
Taoyuan Chungli terrace	1090	47	23.2	94
Taichung area	1180	52	22.7	63
Hengchun plain	110	10	11.0	22
Penghu plain	106	14	7.6	28
Lanyang plain	400	24	16.7	44
Hualien–Taitung valley	930	76	12.2	98
Total	10,546	577	18.3	1071

Table 3 Planned hydrogeologic survey stations and groundwater monitoring wells and implementation stages. (After DWR 1996a)

Stages	Groundwater basin		Number of hydrogeologic survey stations	Number of groundwater monitoring wells
	Name	Area (km^2)		
Stage I (1992–98)	Choshui River alluvial fan	1800	77	175
	Pingtung plain	1130	60	148
	North part of Chianan plain	300	4	9
	Subtotal	3230	141	332
Stage II (1999–2003)	South part of Chianan plain	2220	100	212
	Hsinchu–Miaoli coastal area	900	48	85
	Lanyang plain	400	22	40
	Penghu Island	106	13	25
	Subtotal	3626	183	362
Stage III (2004–08)	Taipei basin	380	27	46
	Taoyuan–Chungli terrace	1090	42	85
	Taichung area	1180	47	57
	Hengchun plain	110	9	20
	Hualien–Taitung valley	930	68	88
	Subtotal	3690	193	296
Total		10,546	517	990

Table 4 Estimated implementation cost for the groundwater monitoring network in Taiwan, in million NT$[a]. (After DWR, 1996a)

Working item	Phase I (1992–98)	Phase II (1999–2003)	Phase III (2004–08)	Total
Hydrogeological survey	565	632	772	1969
Establishment, operations, and management of groundwater monitoring wells	670	1134	1481	3285
Monitoring and survey of land subsidence[b]	51	–	–	51
Planning, establishment, and integration of groundwater information	80	115	130	325
Survey of groundwater area and study of groundwater recharge	148	65	80	293
Analysis and management of groundwater quality	–	166	329	495
Total	1514	2112	2792	6418

[a] The exchange rate in August 1997 was 1 US$ ≈ 26 NT$
[b] This item was shifted to a project entitled "Land Subsidence Prevention Plan in Taiwan" in 1997

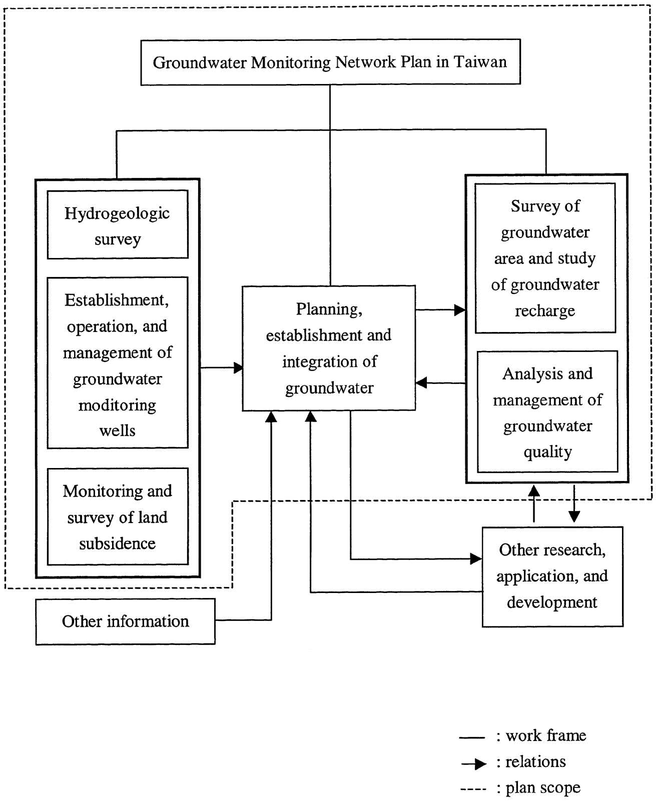


Fig. 3 The scope of the Groundwater Monitoring Network in Taiwan. (After DWR 1996a)

geological surveys; (2) establish groundwater monitoring wells, including operation and management; (3) monitor and survey land subsidence, (4) integrate groundwater information; (5) survey groundwater, including groundwater recharge; and (6) analyze and manage groundwater quality. The relationship among the six work items is shown in *Figure 3*. The details of the plan are as follows:

1. Hydrogeological survey.
   a) Geotechnical drilling. This task includes selection of geologic drilling sites and core sampling, establishment of fence diagrams, and analysis of the layers and depths of major aquifers to determine the number and depth of well screens for monitoring wells.
   b) Hydrostratigraphic classification and geologic stratification. Analysis of the core samples by sediments, fossils, and dating; comparison of geologic layers from each site; and integration of data with geophysics, water-elevation, and water-quality information for geologic stratification are included in this task.
   c) Establishment of a hydrogeologic database and geographic information system (GIS). This task is to establish a hydrogeologic database and GIS to store and process for easy retrieval of the information gathered.
   d) Revision of hydrogeologic fence diagrams. This task is to integrate the results from field experiments and to produce and update hydrogeologic fence diagrams and hydrogeologic maps.
   e) Establishment of a Core Sample Hall to maintain the geologic drilling cores. Since the hydrogeological survey is very expensive, the core samples should be stored for further research in a Core Sample Hall, where the geologic drilling cores would be preserved.
2. Establishment, operations, and management of groundwater monitoring wells.
   a) Installation of groundwater monitoring wells. Land acquisition is the most difficult part of this plan. Design, construction, and establishment of operation rules of monitoring wells are also required.
   b) Installation of an automatic data logger. This task is to design a digital data-collection system that allows groundwater levels and some basic quality data to be collected automatically. All monitoring instruments are of the automatic type and data are recorded on an hourly basis.
   c) Planning and development of a groundwater-hydrology database and geographic information system.
   d) Investigation and analysis of groundwater-related background information. This task includes core sampling; geophysical well logging; single-well pumping tests; dual-well pumping tests; and investigation, analysis, and filing of basic water-quality data.
   e) Analysis of regional groundwater hydrologic characteristics. This task is to integrate the analysis and results from related groundwater studies, define regional groundwater hydrologic systems, define distribution of regional sub-layer parameters, and analyze and investigate regional groundwater sub-layer potentials.
3. Monitoring and survey of land subsidence. This work item focuses on data integration from land-subsidence monitoring and groundwater monitoring wells. Relations between these two databases can be used to analyze the degree of land subsidence and water-table variations. Land-subsidence-monitoring wells installed in different strata are also included in this work item to assist in the understanding of the mechanisms of land subsidence. This work item includes these primary tasks:
   a) Installation of land-subsidence monitoring wells. On the basis of geologic characteristics learned from hydrogeological investigations, select areas with heavy groundwater pumping and construct wells to monitor for land subsidence.
   b) Construct simple cable-type land-subsidence monitoring wells. Use old or abandoned wells to construct simple cable-type land-subsidence monitoring wells.
   c) Data collection and analysis. Survey land subsidence periodically to collect and store data on land subsidence.

Table 5 Installed hydrologic survey stations and groundwater monitoring wells

Category	Area										Total
	Choshui River alluvial fan					Pingtung plain					
	1992	1993	1994	1995	1996	1992	1993	1994	1995	1996	
Hydrogeologic survey station	8	20	25	1	7	–	–	–	15	18	94
Groundwater monitoring wells	17	35	57	–	12	–	–	–	41	44	206
Pumping test wells	3	15	10	–	4	–	–	–	–	15	47
Land-subsidence monitoring wells	6	–	4	–	2	5	–	2	–	2	47

d) Establish a predictive model for land subsidence. Analyze the relations, mechanisms of land subsidence, geological structure, and water-elevation changes to establish models for land-subsidence predictions.
e) Techniques for improvement of land-subsidence surveys. Combine and implement new technology to develop efficient and complete surveys of regional land subsidence.
f) Database establishment. Establish land-subsidence database and information systems to store and process information for easy retrieval.

4. Planning, establishment, and integration of groundwater information.
   a) Integration plan for the framework of groundwater-resource management. This task identifies the research required and forms a working framework in accordance with the integrated

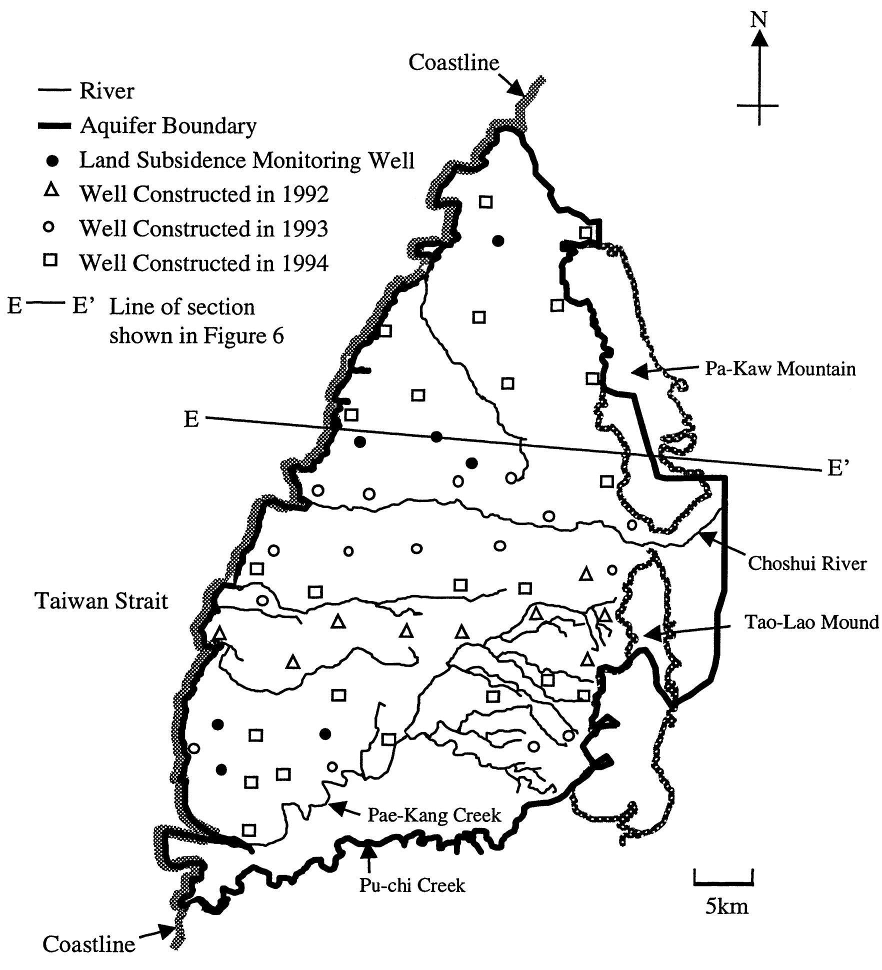
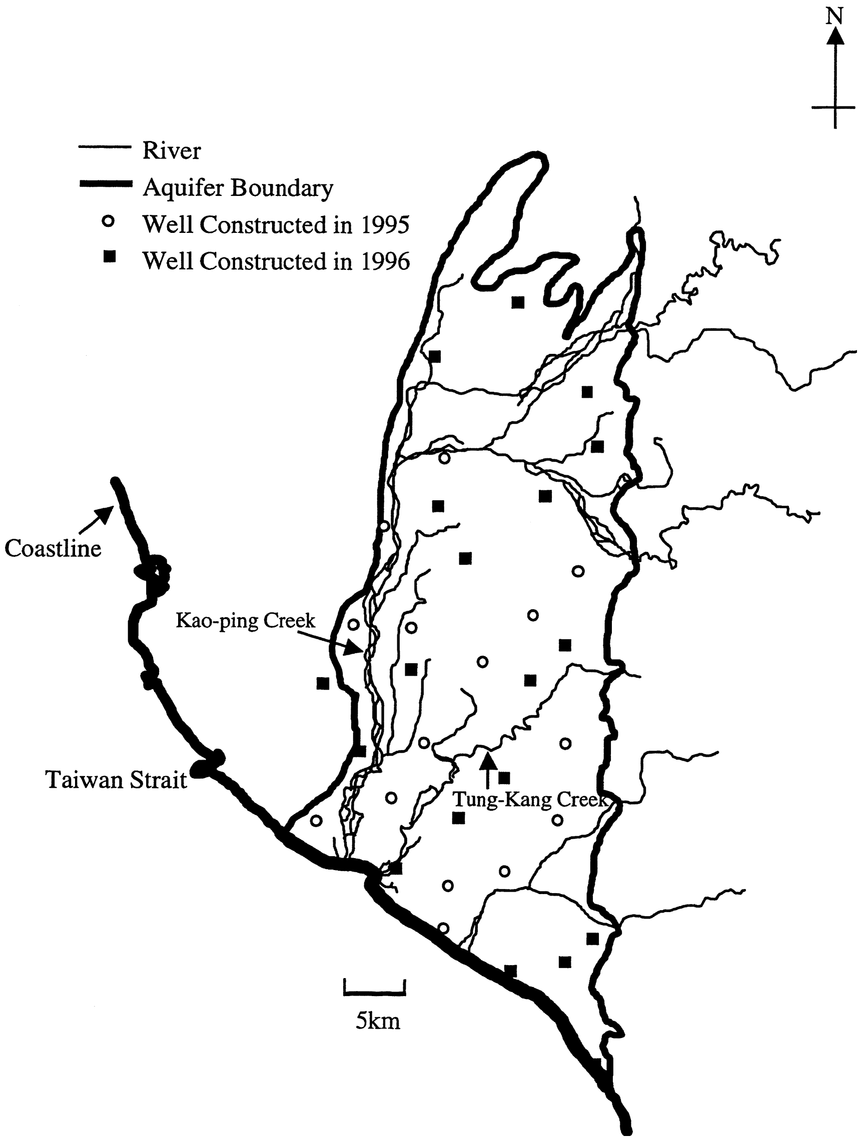


Fig. 4 Locations of constructed hydrogeological survey stations and observation wells in the Choshui River alluvial fan. (After Chiang et al. 1996)

Fig. 5 Locations of constructed hydrogeological survey stations and observation wells in the Pingtung plain (After Chang 1997)



planning of groundwater-resource management of the plan for a groundwater monitoring network.

b) Establishment of an integrated groundwater-resources information system. This task is to establish a supporting system for groundwater-resource policies and an integrated system for maintaining and disseminating groundwater information.

c) Establishment of groundwater GIS. The objectives of this task are to (1) establish a database for wells, water rights, and other related items; (2) integrate all the available data and establish a complete groundwater-resource database; and (3) establish analytical models and tools.

d) Establishment of the interconnection and integration patterns for groundwater information. This task includes storing formats and communication patterns, making it possible to integrate and exchange information on a network.

5. Survey of groundwater areas and evaluation of groundwater recharge.
   a) Integration and analysis of groundwater usage. This task focuses on the general investigation of wells, statistical analysis and in-situ comparison of water-rights data, and estimation of pumping quantity.
   b) Estimation of groundwater potential. In order to estimate groundwater potential, consideration is to be given to allocation of groundwater recharge zones and estimation of the recharge rate, exploration of regional water-balance factors and analysis of water budget, and evaluation of groundwater potential.
6. Analysis and management of groundwater quality. Groundwater quality and quantity are both important for water-resources management. This working item includes the following tasks:
   a) Establishment and management of groundwater-quality index wells. This task is to choose ground-

water-quality index wells, to investigate the nature of groundwater, and to document basic water-quality investigation and analysis from drilling samples.

b) Establishment of a groundwater-quality database. This task is to test and analyze basic water-quality data and to sample wells with unusual water quality.

Preliminary Results

The Groundwater Monitoring Network Plan in Taiwan has been ongoing since 1992. By the end of August, 1996, 94 hydrogeological survey stations and 206 monitoring wells had been constructed. The number of groundwater monitoring wells per year is shown in *Table 5*. Well locations for the Choshui River alluvial fan and Pingtung plain are shown in *Figures 4* and *5*, respectively.

The plan is currently focused on the Choshui River alluvial fan. The preliminary hydrogeologic system of this area has been identified (Chiang et al. 1996). The geometry of the geologic layers and locations for groundwater recharge of the Choshui River alluvial fan have been identified. Tyan et al. (1996) analyzed the groundwater hydrology, aquifer characterization, and groundwater flow pattern in this area. The results obtained by Chiang et al. (1996) and Tyan et al. (1996) are being used for the overall water-resources planning and management in the region.

The preliminary results related to the hydrogeologic survey of the Choshui River alluvial fan are summarized as follows:

1. The groundwater basin is represented by three aquifers and two aquitards, as shown in *Figure 6*. Aquifer II underlies a large portion of the alluvial fan and is mostly water bearing. The large grain size of Aquifer II suggests that it has high hydraulic conductivity.
2. Aquifers I, II, and III probably pinch out in the Taiwan Strait, as shown in *Figure 6*, but this conclusion requires further verification.
3. The aquitards are composed of very fine sands, which contribute to low hydraulic conductivity.

The preliminary results related to groundwater hydrology of the Choshui River alluvial fan are summarized as follows:

1. Hydraulic conductivity ranges from 10^{-3}–10^{-5} m/s, and decreases from the proximal fan to the distal fan. Transmissivity ranges from 0.04–4.19 m^2/min. The storage coefficient is about 0.1 for the unconfined aquifer and ranges from 10^{-3}–10^{-4} for the confined aquifer. The discharge per unit drawdown ranges from 3–128 m^3/m/h.
2. Aquifer II has been subject to over-pumping.
3. The water table fluctuates by as much as 15 m during a given month and 5 m during a given day.
4. The groundwater level declined substantially from 1980 to 1990, but after 1990 the rate of decline slowed.
5. After analyzing the basic water-quality samples for salinity and other parameters, it is concluded that no

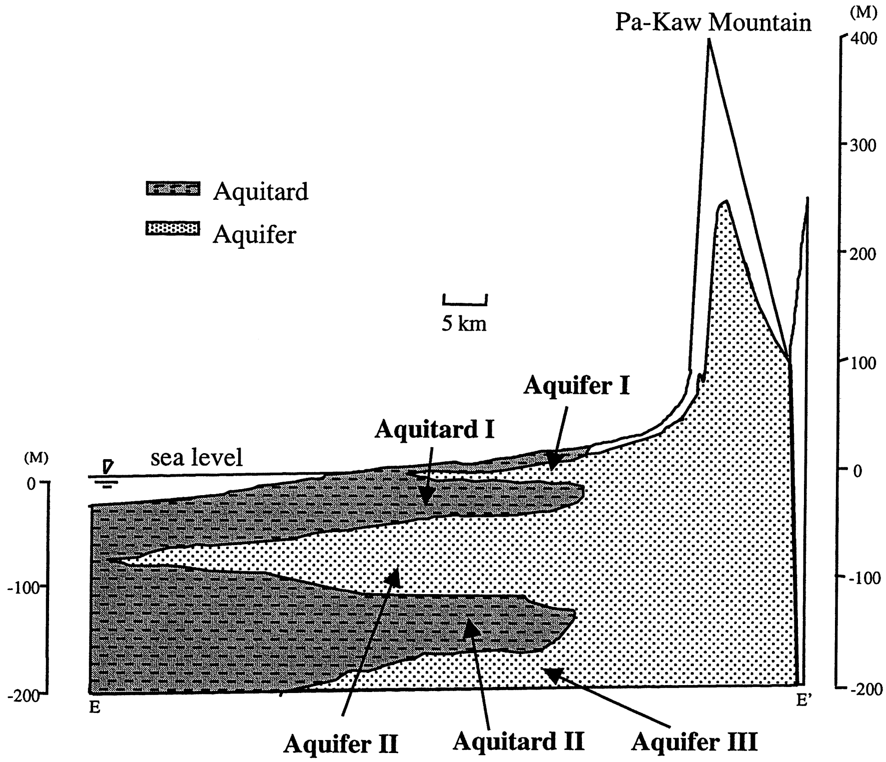


Fig. 6 Conceptual hydrogeologic model of the Choshui River alluvial fan; line of section shown in *Figure 4*. (After Chiang et al. 1996)

seawater intrusion is occurring in the Choshui River alluvial fan.

Conclusions

Development of surface-water resources in Taiwan is limited because of the island's unusual hydrologic and geologic characteristics. The Water Resources Planning Commission reports that the annual groundwater pumping in Taiwan is approximately 7.1 billion m^3. This amount is much greater than the operating storage of all surface reservoirs. The importance of groundwater as a source of water supply has long been recognized, and, in recent years, a concerted effort by the governmental agencies in Taiwan has been undertaken to establish a reliable groundwater monitoring network. The "Groundwater Monitoring Network Plan in Taiwan," set up in 1992, outlines the goals and implementation procedures. This important document in water-resources planning and management is strongly supported by all agencies involved as well as by the people of Taiwan.

The Groundwater Monitoring Network Plan serves two major functions: (1) to gather basic groundwater-hydrology data for land-subsidence mitigation; and (2) to manage and utilize groundwater resources wisely. Data gathered from this plan will contribute to an understanding of "safe yield" of groundwater in many groundwater basins. Although maintaining groundwater monitoring wells requires the commitment of a considerable amount of resources, the current plan is long-term in scope, because monitoring groundwater quantity and quality is becoming increasingly important to the management of future total water resources.

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References

Chang LC (1997) Assessment of the monitoring network for the Pingtung Plain. Project Report, Taipei, Taiwan (in Chinese)

Chiang TJ, Lai DC, Hwang JC, Lai TH, Cheng LC (1996) Hydrogeologic and groundwater conceptual model of the Choshui River alluvial fan. In: Proc of the National Groundwater and Hydrogeologic Conference on the Choshui River Alluvial Fan. Taipei, Taiwan, pp 127–143 (in Chinese)

DWR (Department of Water Resource), Ministry of Economic Affairs (1996a) Groundwater monitoring network plan in Taiwan. Taipei, Taiwan (in Chinese)

DWR (Department of Water Resources), Ministry of Economic Affairs (1996b) Reservoirs and dams in Taiwan. Taipei, Taiwan (in Chinese)

Hsu SK, Liu FS, Cheng CC, Hsu NS, Tsay TS (1996) A master plan for the groundwater network in Taiwan. In: Proc Science, Engineering and Technology Seminars, Technology Innovation and Integration, Texas, USA

TPWCB (Taiwan Provincial Water Conservancy Bureau) (1988–92) Improving the groundwater hydrological data collection system in Taiwan. Taipei, Taiwan (in Chinese)

Tyan CL, Lin WK, Chang YM, Tsai MK (1996) The brief introduction to the groundwater hydrology of Choshui River alluvial fan. In: Proceedings of the National Groundwater and Hydrogeologic Conference on the Choshui River alluvial fan. Taipei, Taiwan, pp 207–222 (in Chinese)

WRPC (Water Resources Planning Commission), Ministry of Economic Affairs (1989) Water resources: groundwater utilization and conservation in Taiwan, Republic of China. In: The Eleventh Board Meeting of the Advisors for Science and Technology, the Executive Yuan. Taipei, Taiwan

WRPC (Water Resources Planning Commission), Ministry of Economic Affairs (1996) Groundwater in Taiwan. Taipei, Taiwan

Wu CM (1992) Ground water development and management in Taiwan. J Geol Soc China 35(3):293–311

Wu CM (1994) Regional water resources development and planning in Taiwan, Republic of China. Water Resources Planning Commission, Ministry of Economic Affairs, Taipei, Taiwan