

$^{87}\text{Sr}/^{86}\text{Sr}$ ratio: a natural tracer to monitor groundwater flow paths during artificial recharge in the Bangkok area, Thailand

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Abstract The aquifer system in the Thon Buri sedimentary basin below the deltaic flood plain of the Chao Phraya River, central Thailand, has been exploited for public water supply for the capital Bangkok since the early 1920s. Groundwater withdrawal, currently 1.4 million m^3/d , has resulted in a maximum decline in hydraulic head of up to 40m. This has induced land subsidence of as much as 1.7m (1940–1992) in the eastern suburbs of the metropolis. Artificial injection of purified water within an area-wide network of recharge wells could constitute a remedy to slow the water level depression within the sedimentary basin, and thus the subsidence. This requires a prior shutdown of water withdrawal. The flow paths of the injected water can be traced by changes in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the groundwater and injected water mixture within the three main aquifers in the basin that are used for public supply. The ratios, monitored at five monitoring stations within the cone of depression, have been constant over 3 years. Injection of the calculated cone volume of $5.2 \times 10^9 \text{ m}^3$ would take at least 10 years, depending on the injection pressure and the number and position of wells.

Résumé Le système aquifère du bassin sédimentaire de Thon Buri sous la plaine d'inondation du delta de la

rivière Chao Phraya, au centre de la Thaïlande, a été exploité pour l'alimentation publique en eau de la capitale Bangkok depuis les années 1920. L'exploitation de l'eau souterraine, pour l'instant 1.4 million de m^3/j , a conduit à une diminution maximum de 40mètres de la charge hydraulique. Ceci a induit un effondrement du niveau du sol suburbain dans la partie est de la métropole. L'injection artificielle d'eau traitée dans un réseau de puits de recharge à l'échelle de la zone pourrait constituer un remède pour ralentir la dépression dans le bassin sédimentaire, et donc également l'effondrement des sols. Ceci nécessite un arrêt préliminaire du prélèvement de l'eau. Les trajets de l'écoulement des eaux injectées peut être tracé en suivant les changements du rapport $^{87}\text{Sr}/^{86}\text{Sr}$ de l'eau souterraine et du mélange des eaux injectées dans les trois principaux aquifères du bassin, utilisés pour l'alimentation publique. Les rapports, suivis dans cinq stations de surveillance dans le cône de rabattement, sont restés constants durant 3 années. L'injection du volume du cône de rabattement, soit $5.2 \times 10^9 \text{ m}^3$, prendrait au moins 10 ans, selon la pression de l'injection et le nombre et la position des puits.

Resumen El sistema acuífero en la cuenca sedimentaria de Thon Buri, debajo de la llanura de inundación deltaica del Río Chao Phraya, Tailandia central, se ha explotado para el suministro público de agua en la capital Bangkok, desde los comienzos de 1920s. La extracción de agua subterránea, actualmente 1.4 millones de m^3/d , ha producido un declive máximo en la cabeza hidráulica hasta de 40m. Esto ha inducido la subsidencia del terreno tanto como 1.7m (1940–1992), en los suburbios orientales de la metrópoli. La inyección artificial de agua purificada dentro de una red amplia de pozos de recarga, podría constituir una corrección para retardar la depresión del nivel del agua, dentro de la cuenca sedimentaria, y así mismo la subsidencia. Esto requiere una suspensión previa de la extracción de agua. Las direcciones de flujo del agua inyectada pueden ser seguidas por los cambios en la proporción $^{87}\text{Sr}/^{86}\text{Sr}$ del agua subterránea y de la mezcla de agua inyectada, dentro de los tres acuíferos principales en la cuenca que se usa para el suministro público. Las proporciones, monitoreadas en cinco estaciones para este fin, dentro del cono de depresión, han sido constantes por más de 3 años. La inyección del volumen del cono calculado de $5.2 \times 10^9 \text{ m}^3$, tomaría 10 años por lo menos,

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dependiendo de la presión de inyección y del número y posición de los pozos.

Keywords Bangkok · Subsidence · Strontium · Tracer tests · Artificial recharge

Introduction

The deltaic flood plain of the Chao Phraya River in central Thailand is the second largest river delta in southeastern Asia after the Mekong delta, Vietnam. It drains the Central Plain (Fig. 1), which has several sedimentary basins, and is the receiving stream for several rivers that drain the highlands and ranges in the hinterland. The basin located underneath the Bangkok area is the Thon Buri sedimentary basin, created by block

faulting in the late Pliocene to Pleistocene. The position of Bangkok within the Lower Central Plain causes many problems as a result of the high water-withdrawal rate from the three Thon Buri Basin aquifers that are used for public water supply. The whole aquifer system holds a total of eight aquifers (Fig. 2).

Since the withdrawal started in the early 1920s, the increasing pumping rates (up to 1.4 million m³ in 1992; Ramnarong and Buapeng 1992a) have led to a decline in the hydraulic head, occasionally of 3.6 m/year. The levels prior to withdrawal in the 1920s were about 4 m below land surface (bls); recently they have been greater than 50 m bls in central Bangkok and its eastern suburbs (Ramnarong and Buapeng 1992a). Figure 3 shows the depression in hydraulic head. There is evidence that this weakens the internal structure of the aquifer system within the Thon Buri Basin. Thus, the ground surface has undergone continuous subsidence by as much as 1.7 m in the eastern suburbs between 1940 and 1992 (Ramnarong and Buapeng 1992a). According to Phien-wej et al. (1989), the subsidence rates vary between 0 and 10 cm/year throughout the Bangkok metropolitan area, which entails different settlement rates of buildings, e.g. foundation walls of temples, sidewalks and bridges. Some places are now located below sea level, and are thus affected by flooding because sea water and river water flow into the land depression.

The subsidence problem can be addressed in two ways, which lead to different results for the people and the environment:

1. End of pipe solutions

These actions directly combat the secondary problems of damages and flooding, which are obviously of concern for the population. In the Bangkok area, several different remedial steps are performed routinely. For example, shopping malls add new steps to their entrances because the streets subside. Dams are built to reduce flooding. These actions only deal with the results of the initial problem.

2. Beginning of pipe solutions.

Several actions have been proposed to tackle the underlying problem of overexploitation of the aquifers. The first action proposed is to reduce or to completely stop the water withdrawal. The water supply can be managed by using treated surface water, which may, however, be more expensive than using groundwater. Water-supply fees will have to be raised in the future in the Bangkok area as a result to the water-supply problem. After cessation of the groundwater withdrawal, the hydraulic head will increase through natural recharge. This process might take an unacceptably long time because the groundwater flow through the Lower Central Plain probably has taken more than 10,000 years, as shown in a paleoflow simulation by Sanford and Buapeng (1996). To shorten this recharge time, surface water can be directly injected into the aquifers in the cone of depression. According to the Department of Groundwater

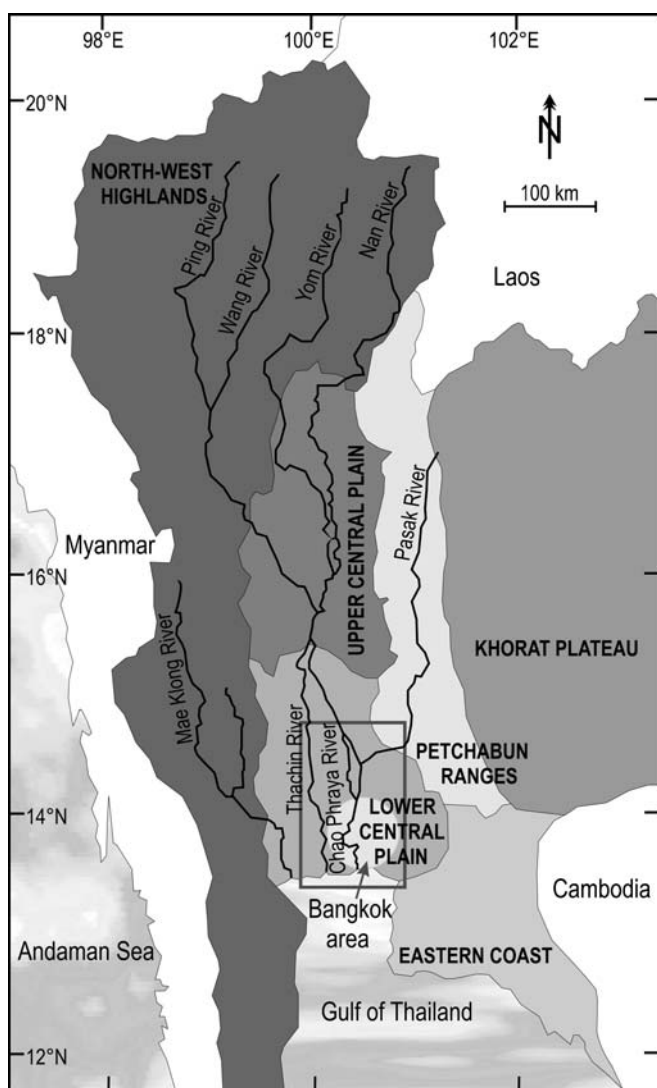


Fig. 1 Landforms of central Thailand; the Lower Central Plain is the catchment area of the Chao Phraya River and the Thon Buri sedimentary basin underneath Bangkok; the Bangkok area, depicted by the white circle, is shown in Fig. 3 (modified after Sinsakul 2000)

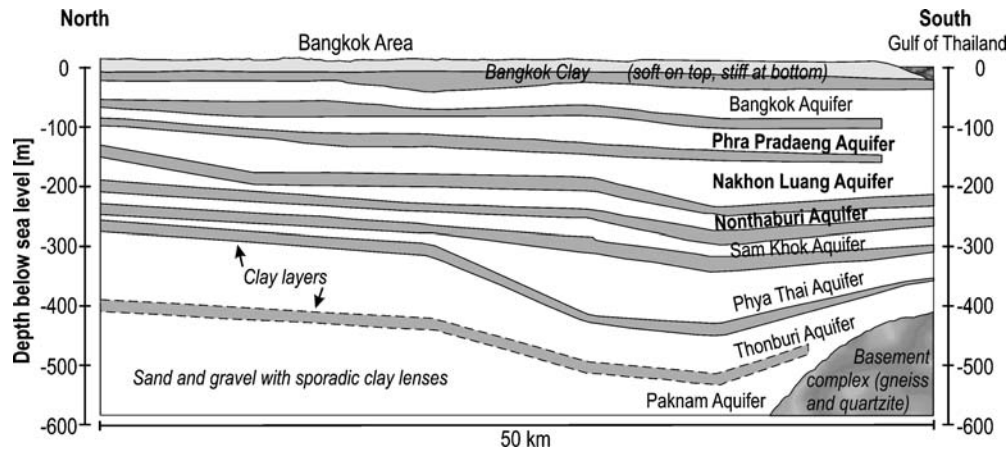


Fig. 2 Hydrogeologic section through the Thon Buri sedimentary basin beneath Bangkok; groundwater for public water supply is extracted from the aquifers Phra Pradaeng, Nakhon Luang and Nonthaburi; for location see Fig. 4 (modified after Phien-wej et al. 1989)

Resources in Bangkok, one source of suitable water for this artificial recharge could be the Mae Klong River which drains the western highlands (Fig. 1). The water quality is good in comparison to the water of Chao Phraya River, which travels through Bangkok. The Mae Klong catchment area is small and located in the highlands. A high gradient produces fast water flow to the Gulf of Thailand with an average runoff rate of 13 km³/year.

Injection tests performed previously in the Bangkok area (Ramnarong 1973) provide a database of physical parameters and a framework that can be taken into account for a theoretical model to trace the water flow paths during and after injection. The idea is to monitor the change in the isotopic strontium ratio, $^{87}\text{Sr}/^{86}\text{Sr}$, before injection and after groundwater and surface water are mixed in the aquifers. Preconditions are constant $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of (1) groundwater at the observation wells, and (2) surface water destined for injection. Strontium isotopes are suitable tracers because they occur naturally and are neither affected by geological processes nor subject to fractionation (Wedepohl 1978). Strontium isotopes ratios, as a tracer method in groundwater systems, were successfully used in several hydrological studies, e.g. in Canada, USA, Germany (McNutt et al. 1990; Bullen et al. 1996, 1997; Katz and Bullen 1996; Armstrong et al. 1998; Negré 1999; Peterman and Wallin 1999; Wiegand et al. 2001).

The aim of this study is to find out if the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater in the aquifers beneath Bangkok are constant, and thus of use for a future artificial recharge project. For that purpose, the Department of Groundwater Resources chose five monitoring stations within the municipal groundwater observation network of 103 stations (Fig. 4) to determine Sr concentrations over a 3-year period. The five sampling stations are located inland of the cone of depression (Fig. 3), to minimize sea-water influence. All stations comprise three wells, one for each of the three aquifers that are in use for public water supply. The boreholes are perforated in sections of 6–7 m at around 100 m below surface for the Phra Pradaeng

aquifer, around 150 m for the Nakhon Luang aquifer, and around 200 m for the Nonthaburi aquifer (Fig. 2).

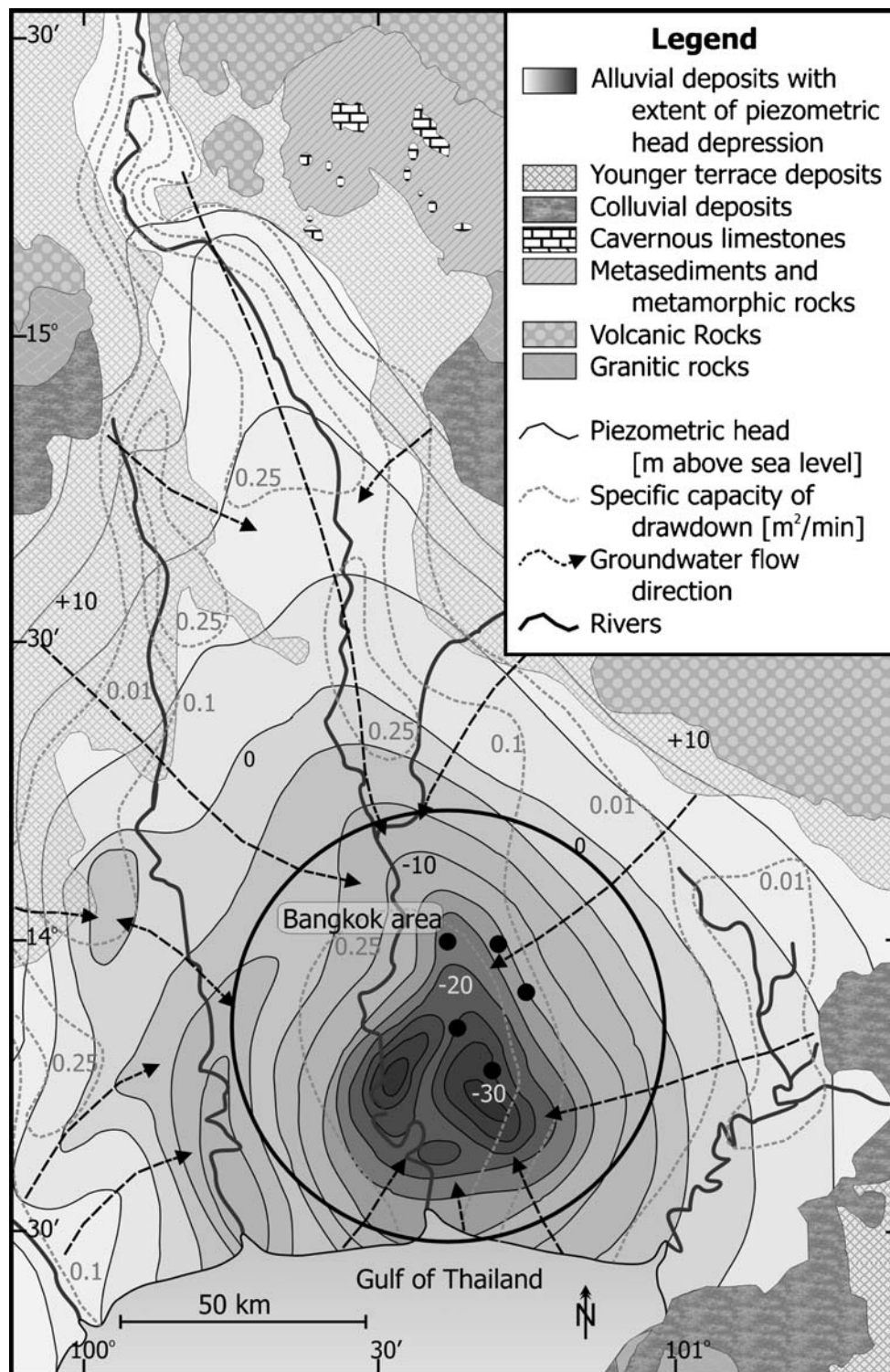
Geology and hydrogeology of the Thon Buri Basin

The Thon Buri sedimentary basin, from which the groundwater is extracted, extends about 175 km to the north, 60 km to the west and 20 km to the east of Bangkok. The basin is formed by a halfgraben structure, created by block faulting under influence of the Three Pagoda fault zone in the late Pliocene to Pleistocene (Fig. 5; Sinsakul 2000). Figure 2 shows the upper 600 m of the basin sediments, including eight artesian aquifers of sand and gravel (Phien-wej et al. 1989) alternating with aquitards of confining stiff clay. The sequence comprises seven stratigraphical units (Chaodumrong and Chaimanee 2002), starting with a quartzitic basement which is overlain by four fluvialite pre-faulting units deposited conformably and disconformably from the Oligocene to Miocene Epochs. The sixth unit of varying post-faulting Quaternary sediments is superimposed by the Bangkok Clay (Holocene) deposited 8,000–2,000 years ago (Saito et al. 2002).

The aquifer system is recharged by rainwater, mostly in the rainy season, through the outcrops at the margins of the basin, with a share of only 3.2% of the annual rainfall volume in this area (AIT and DMR 1982), and by infiltrating river water. Direct vertical recharge of rainwater through the Bangkok Clay is rarely observed.

According to Ramnarong and Buapeng (1992a), the general flow directions of groundwater below the Central Plain are to the south, the southeast and southwest. A flow velocity of 0.4 m/d was calculated from ^{14}C -data (Sanford and Buapeng 1996). Thus, the water movement from the recharge areas in the hinterland to the Gulf of Thailand takes more than 10,000 years. Recently, the cone of piezometric depression below the Bangkok area lead to a reverse flow of water landwards from the sea (Fig. 3), accompanied by sea-water intrusion through the coastal

Fig. 3 The Lower Central Plain under hydrogeological aspects (excerpted from Fig.1); the *black dots* are the five sampling stations landwards from the cone of depression (modified after Ramnarong and Buapeng 1992a, and Piancharoen and Chuamthaisong 1976)



sediments. The first indications for sea-water intrusions were observed in 1960 at the nearshore wells (Piancharoen and Chuamthaisong 1976).

The Phra Pradaeng, the Nakhon Luang and the Non-thaburi aquifers consist of subrounded to rounded, poorly sorted sand and gravel, alternating with compact clay layers (Piancharoen 1972; Ramnarong and Buapeng 1992a). The Nakhon Luang aquifer is the most exploited. Hydraulic

connections between the aquifers allow water to move into the Nakhon Luang aquifer (Sanford and Buapeng 1996).

Sampling locations and analytical methods

At each of the five sampling stations (Nos. 16, 22, 66, 73 and 97 in Fig. 4), wells reaching the aquifers Phra

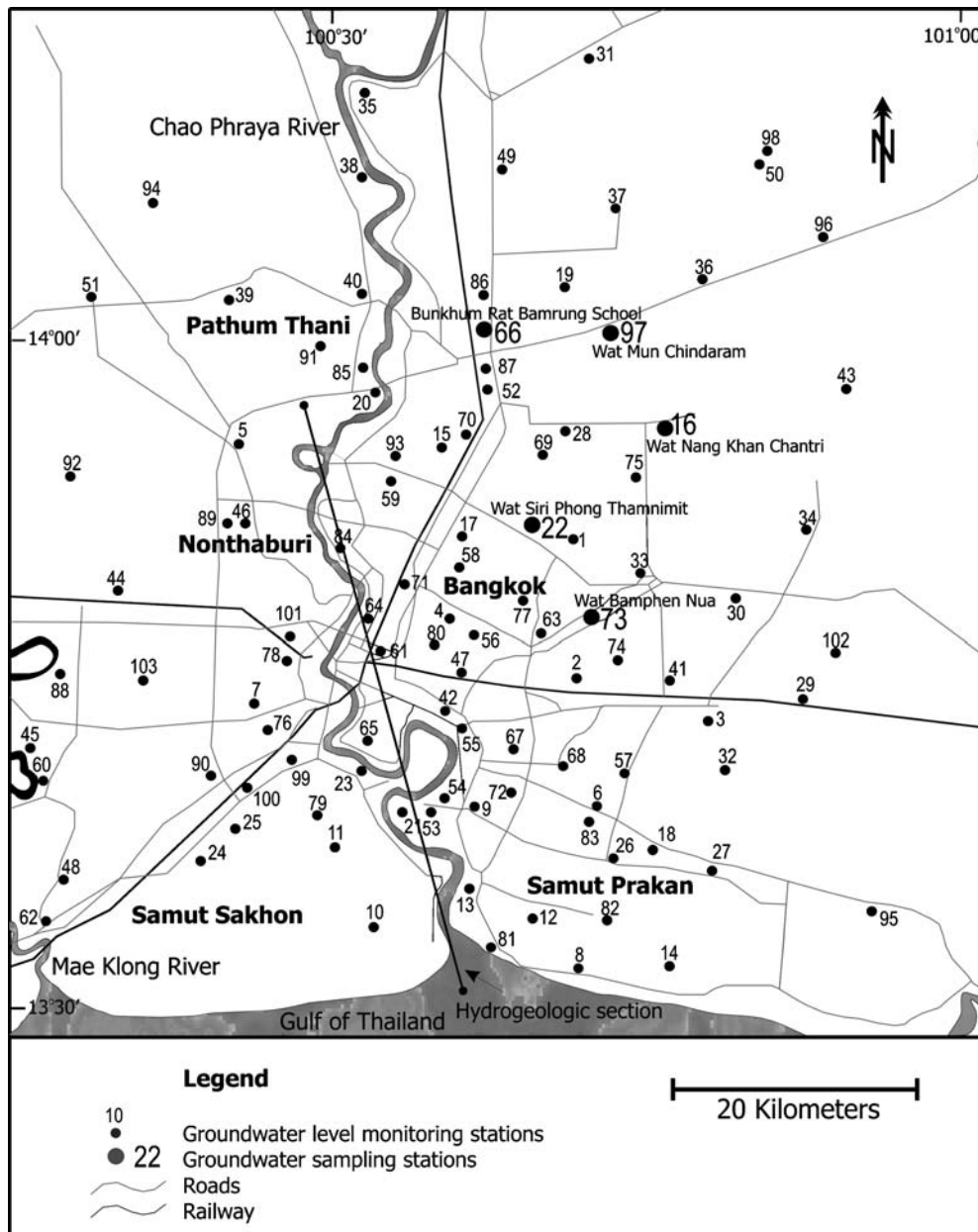


Fig. 4 Map of the provinces in the Bangkok area with locations of the groundwater monitoring stations; the five sampling stations (16, 22, 66, 73 and 97) are highlighted; the hydrogeologic section is shown in Fig. 2 (modified after DMR 1994)

Pradaeng (PD), Nakhon Luang (NL) and Nonthaburi (NB) are available, from which a total of 56 samples were collected during three dry and two rainy seasons between December 2000 and July 2003. Sampling at station No. 16 ceased after two seasons due to leakage of the pipe. In addition, 19 samples were collected from the utility raw-water tap (GW, mixed groundwater from all three aquifers at one site), from small lakes (LW) nearby the sampling stations, from tributaries (“khlongs”) of the Chao Phraya River (KW) and from rainwater (RW).

For groundwater sampling, a pump with a pipe was dropped down into the well, fixed below the water level and operated for 30 min to rinse the pipe and the bore case. A 500-ml sample was collected with a plastic beaker,

filtered through a CA membrane filter of 0.45 μm and acidified with 3% distilled HNO_3 (65%).

For the strontium isotopic analysis, all water samples were diluted with an Rb–Sr double spike prior to conversion to the chloride form with distilled 6N HCl. After drying the samples, they were dissolved in 2.5N HCl as eluent, and Sr was extracted by columnar elution using 5 ml quartz-glass columns filled with the cation resin Bio-Rad AG 50W-X8, 200–400 mesh (for method see also Wiegand et al. 2001). The collected eluate was dried and finally dissolved in 1 μl of 0.25N H_3PO_4 and loaded on Re-double filaments. The Sr-isotopic compositions were measured at the Geoscience Center of the University of Göttingen, Germany (GZG) with a Finnigan

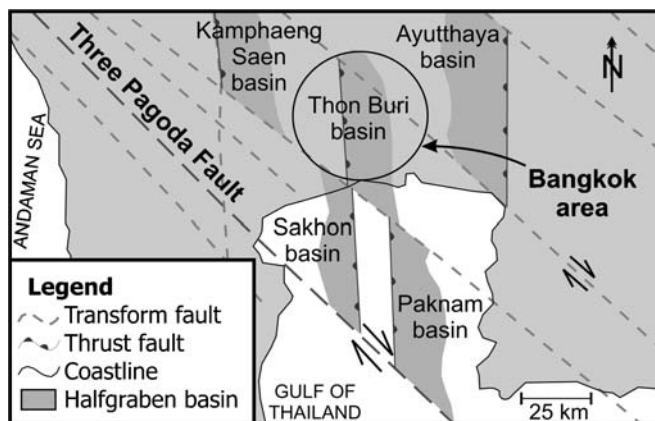


Fig. 5 The fault system in central Thailand with the *Thon Buri Basin* below Bangkok and surrounding sedimentary basins (modified after Chaodumrong and Chaimanee 2002)

TRITON thermal ionization mass spectrometer. The values obtained for the NBS 987 interlaboratory reference material are 0.710252 ± 0.000006 ($n=20$). The major elements were analyzed with an inductively coupled plasma optical emission spectrometer at the GZG.

Major elements and sea-water intrusion

The major element concentrations in groundwater, and their ratios, are assumed to match the characteristics of the aquifer matrix (Johnson 1966). In the Thon Buri Basin, they are influenced by sea-water intrusion into the groundwater body, observed since 1960. Along with the data collected as part of this study, older data sets (1978–

1998) within the monitoring network were reviewed and utilized for evaluation of the long-term evolution of the water quality (for further interpretation, station 16 is neglected due to leakage of the pipe).

The decrease in water quality was represented by an increase in concentrations of chloride, iron, manganese, sulfate, calcium, sodium, magnesium, hardness and total dissolved solids (TDS; Ramnarong and Buapeng 1992a). The sea-water intrusion is limited to the three aquifers (Fig. 2) which are mainly used for water withdrawal (Ramnarong and Buapeng 1992b). Since the annual withdrawal exceeds the natural recharge, a continuous transition zone with a steady-state interface between fresh water and salt water is unlikely. Even in cases where withdrawal equals recharge, vertical displacements of the interface are observed (Tadolini and Tulipano 1991). Thus, a spatial discontinuous propagation of sea-water intrusion can be assumed. Varying pumping rates in different parts of the Bangkok area and the general tendency of water to move towards the center of the cone of depression (Fig. 3) may intensify mixing of fresh and sea water.

The distribution of TDS values within the five stations is shown in Fig. 6. According to the classification of Lloyd and Heathcote (1985), 80% of the values of the Phra Pradaeng aquifer can be classified as brackish water (TDS=1000–10000 ppm); 16% are within this range for the Nakhon Luang aquifer, and only 13% for the Nonthaburi aquifer (not considering the obviously leaking pipe at station 16). All other values (except two from station 16, Nonthaburi aquifer, which are saline) are below 1,000 ppm. Thus, the portion of fresh water (TDS=0–

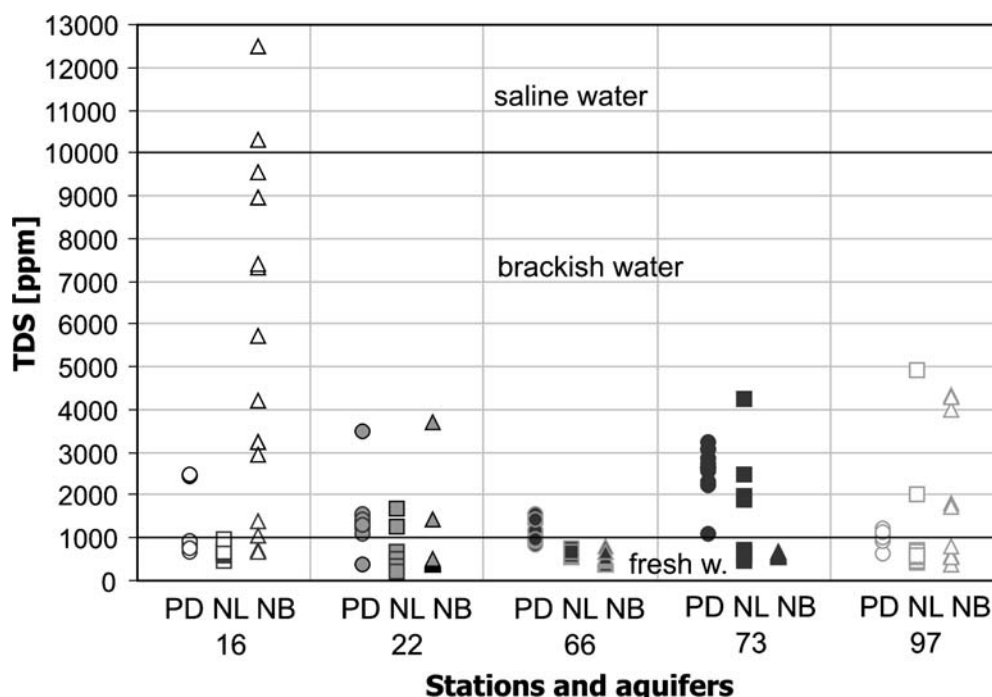


Fig. 6 The distribution of total dissolved solids (TDS) within the three aquifers Phra Pradaeng (PD), Nakhon Luang (NL) and Nonthaburi (NB) at the five sampling stations

1,000 ppm) seems to increase downwards with decreasing sea-water influence.

Sr substitutes for Ca (Matthess 1994) due to an almost similar ionic radius of 1.00 Å and 1.16 Å, respectively, and their position in the second group of the periodic classification of elements. Hence, the evolution of the Sr concentration within the aquifers is directly related to the Ca evolution. They show a positive correlation with a correlation coefficient of 0.97.

Exchange of ions between intruding sea water and the aquifer matrix can change the cation content of the mixture (Appelo and Postma 1999). The dominant ions in fresh water are mainly Ca^{2+} and HCO_3^- , whereas in sea water, the predominating ion content consists of Na^+ and Cl^- . Under fresh-water influence, materials within the aquifer matrix such as clay minerals, organic matter and oxides/hydroxides, adsorb the Ca^{2+} on their surfaces. During sea-water intrusion, the Ca^{2+} is exchanged by Na^+ , and thus Ca^{2+} (and also Sr) is released. This leads to a surplus in Ca^{2+} and a displacement of NaCl-water by CaCl_2 -water, which seems to occur in this case, as shown in the Piper diagram (Fig. 7). In the rhombus, the mixing line between fresh water, $\text{Ca}(\text{HCO}_3)_2$, and sea water (NaCl) is indicated. The sea-water influence increases to the top (CaCl_2). The four highlighted hydrochemical

facies of groundwater (Back 1961) can help to classify the aquifer characteristics:

(A)	Na- HCO_3	Fresh-water characteristics
(B)	Na- HCO_3 -Cl	Increasing salt-water influence
(C)	Na-Cl	Highest salt-water influence
(D)	Ca-Na-Cl	Salt-water intrusion

The Phra Pradaeng water comprises the facies D, C and B, all four facies for the Nakhon Luang, and the Nonthaburi facies C, B and A. Thus, the development of the intrusion front indicated by the CaCl_2 -type water seems to decrease with depth. The increasing portion of fresh water with depth results in lower releasing rates of Ca and also Sr at the cation exchange sites. Therefore, a decrease of the Ca- and Sr concentrations occurs with depth.

The decreasing influence of NaCl-water is also correlated to an increasing pH: in general, a surplus in Ca^{2+} in water leads to calcite precipitation (in Fig. 7, above the two-component mixing line), resulting in low pH due to a lower buffering capacity. Water below the mixing line is affected by calcite dissolution due to a lack of Ca^{2+} , leading to a high pH (Appelo and Postma 1999). The groundwater from the three sampled aquifers mirror this

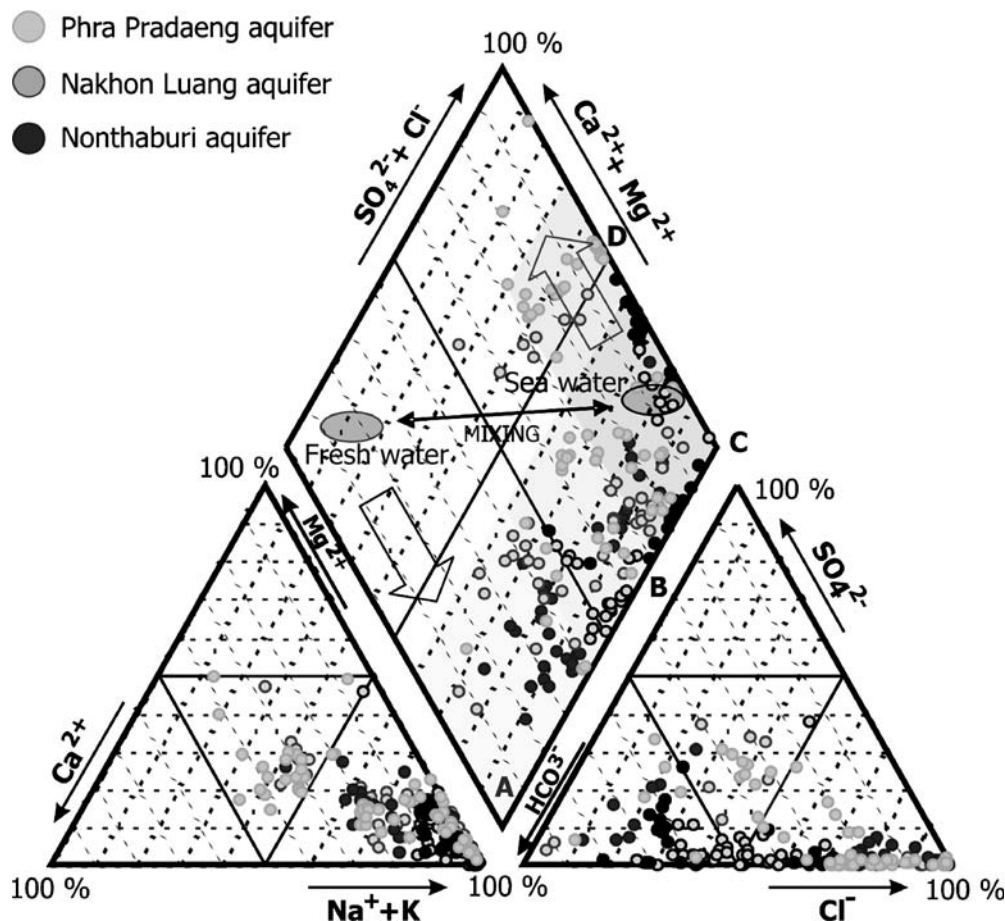


Fig. 7 Diagram after Piper (1944) showing ion data (regularly monitored 1978–1998, Buapeng and Lorphensri 1999) from the three aquifers used for public-water supply. The highlighted hydrochemical facies (A, B, C, D) are described in the text

trend with the lowest pH (7–8) in the uppermost Phra Pradaeng aquifer, a medium pH (7–9) in the Nakhon Luang aquifer, and the highest pH (up to 10) in the Nonthaburi aquifer.

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and usefulness as a natural tracer

The time-dependent change of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is useful as a tracer for water flow paths during/after injection. The evolution of Sr in groundwater depends on its origin and combines regional and global aspects. The global water cycle contains several sources and sinks for strontium in the oceans, on or in the continents, and in the atmosphere. Faure (1986) quoted the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Earth's homogeneous mantle to be 0.702–0.705. The crust shows higher and more variable values around 0.710 due to the higher rubidium/strontium (Rb/Sr) ratios of siliceous rocks.

Wadleigh et al. (1985) calculated the modern Sr budget of the oceans by including (1) the flux from the continents through the rivers (Brass 1976, Durum and Haffty 1963, Holland 1978, Martin and Meybeck 1979), (2) the mantle flux from sea water–basalt interactions (Albarède et al. 1981, Hoffman and Hart 1978), and (3) the porewater flux from seafloor diagenetic processes (Elderfield and Gieskes 1982); in the Wadleigh et al. (1985) study, the appropriate $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were taken into account. According to Burke et al. (1982) the modern $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the ocean is 0.70907, as a result of a semi-linear increase since the Late Jurassic (then 0.7068). The Sr concentration of modern sea water is about 7,700 ppb (Faure 1986).

The Earth's atmospheric influence depends on location, due to anthropogenic impacts, dust particles and different evaporation values. In this study, the atmospheric $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are represented by the ratios in rainwater (e.g. Graustein and Armstrong 1983).

The average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in global continental runoff was estimated by Palmer and Edmond (1989) as 0.7119, and the calculation included the Chao Phraya River (0.7138) and the Mae Klong River (0.7164).

The huge diversity of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, coming from different water–rock-interaction provinces, precludes a general formula for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in groundwater. Thus, the regional circumstances are the crucial factor, and this applies equally to the Thon Buri Basin. To address these regional factors, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the Bangkok area have to be considered.

1. *Groundwater (56 samples)*. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of groundwater from the three aquifers Phra Pradaeng, Nakhon Luang and Nonthaburi range between 0.7069 and 0.7095 (Table 1). In general the range might be in-between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of:

- (a) The Oligocene limestone deposits in the Thon Buri Basin, which should reflect a sea-water ratio of ≥ 0.7077 (Burke et al. 1982) at time of deposition

- (b) The sea-water ratio of 0.70907

- (c) The ratios for continental crust, runoff and river water (CRR) of 0.710 and above

The succession of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is station 97 < limestone < station 66 < station 73 < sea water < station 22 < CRR (Fig. 8), which is also a general trend in the direction to the Gulf of Thailand (Fig. 9) and to the siliceous basement complex which is protruding up to about 400 m below the Gulf (Fig. 4).

The variation in the groundwater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios over the 3 years of sampling is only $\sim 0.1\%$ for stations 22, 66 and 73, and up to $\sim 0.3\%$ for the stations 16 and 97. The variation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of each of the three aquifers at each station is between $\sim 0.01\%$ (similar to 2σ error) and $\sim 0.3\%$ (Table 1).

The Sr concentrations of the groundwater samples in Fig. 8 range between 8 ppb and 2,757 ppb (Table 1). They increase within the stations 97 < 66 < 22 < 73, almost similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, towards the sea-water concentration. The stations 22, 73, and partly also 66, show a general trend of decreasing concentrations with depth. Station 97 comprises generally low concentrations of up to 864 ppb. Seasonal variations seem to occur periodically within specific wells, mainly within the Phra Pradaeng well and the Nakhon Luang well of the stations 66 and 73. The dry season 2000/2001 shows high Sr concentrations, followed by lower concentrations in the rainy season of June 2001. The seasons of other years partly describe this trend. Hence, the Sr content seems to decrease generally from the dry to rainy season.

2. *Tap water (GW, mixture of groundwater from all aquifers, ten samples)*. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of raw tap water range between 0.7069 and 0.7093. The only complete data set, at station 97, shows low variation. The Sr concentrations vary from 212 ppb to 950 ppb (one outlier with 4,000 ppb). Only station 97 shows reasonably constant Sr concentrations.
3. *Lake- (LW) and khlong (KW) water (six samples)*. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of lake water and khlong water range between 0.7069 and 0.7097. The Sr concentrations show high variation from 174 ppb to 7,727 ppb. In general, the concentration seems to increase towards the Gulf of Thailand, and in comparison with the sea-water concentration of 7,700 ppb (Faure 1986), the sea-water influence on the shallow waters increases the Sr concentration up to the maximum of 7,727 ppb.
4. *Rainwater (RW, three samples)*. The three rainwater samples show significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7100, 0.7103 and 0.7113) than the other three water types. The concentrations of Sr are very low with values of 2–3 ppb. Therefore, the observed dilution of the groundwater by rainwater during the rainy seasons can decrease the Sr concentration, but should have no influence on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

The comparison of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with major element ratios can help to distinguish between the weathering input of different rock types in groundwater. Strontium isotopes are not fractionated during weathering processes, and element ratios are more conservative than concen-

Table 1 Sr results for the five seasons studied

Type	Station	1. Season dry 2000/ 2001	2. Season rainy 2001	3. Season dry 2001/ 2002	4. Season dry 2002/2003	5. Season rainy 2003	$^{87}\text{Sr}/^{86}\text{Sr}$ -range per well (only from aquifer values)	$^{87}\text{Sr}/^{86}\text{Sr}$ -range per station	SD per well	SD per station
		$^{87}\text{Sr}/^{86}\text{Sr}$ $\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$ $\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$ $\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$ $\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$ $\pm 2\sigma$				
GW	16	0.70734 $\pm$ 3 237	0.70702 $\pm$ 3 247							
PD		0.70704 $\pm$ 1 880	0.70811 $\pm$ 6 21							
LW	22	0.70971 $\pm$ 3 7,727								
GW				0.70836 $\pm$ 1 808						
PD		0.70929 $\pm$ 2 2,020	0.70932 $\pm$ 3 1320	0.70929 $\pm$ 1 1,911	0.70933 $\pm$ 2 2005	0.70932 $\pm$ 1 1,536	0.00004		0.00002	
NL		0.70912 $\pm$ 2 2,471	0.70951 $\pm$ 2 731	0.70901 $\pm$ 2 2,347	0.70949 $\pm$ 1 663	0.70951 $\pm$ 3 683	0.00050		0.00024	
NB		0.70928 $\pm$ 2 232	0.70941 $\pm$ 2 991	0.70932 $\pm$ 2 236	0.70927 $\pm$ 1 199	0.70933 $\pm$ 1 224	0.00014	0.00050	0.00006	0.00013
GW	66	0.70789 $\pm$ 0.4	0.70839 $\pm$ 5 950							
PD		0.70785 $\pm$ 3 2,198	0.70801 $\pm$ 3 630		0.70804 $\pm$ 1 814	0.70811 $\pm$ 1 1,383	0.00026		0.00011	
NL		0.70801 $\pm$ 1 2,180	0.70802 $\pm$ 2 765		0.70802 $\pm$ 1 1996	0.70798 $\pm$ 1 1,268	0.00004		0.00002	
NB		0.70855 $\pm$ 3 1,235	0.70851 $\pm$ 3 110		0.70848 $\pm$ 1 126	0.70840 $\pm$ 5 99	0.00015	0.00070	0.00007	0.00025
LW	73	0.70794 $\pm$ 1 1,798								
PD		0.70890 $\pm$ 2 2,757	0.70889 $\pm$ 5 2,187	0.70885 $\pm$ 1 2,117	0.70884 $\pm$ 1 2247	0.70883 $\pm$ 1 1,913	0.00009		0.00003	
NL		0.70859 $\pm$ 1 545	0.70865 $\pm$ 6 464	0.70857 $\pm$ 1 471	0.70860 $\pm$ 1 356	0.70854 $\pm$ 3 324	0.00011		0.00004	
NB		0.70886 $\pm$ 2 81	0.70880 $\pm$ 1 103	0.70880 $\pm$ 2 233	0.70882 $\pm$ 1 134	0.70878 $\pm$ 1 133	0.00008	0.00036	0.00003	0.00013
LW	97	0.70927 $\pm$ 2 212	0.70893 $\pm$ 4 174							
GW		0.70693 $\pm$ 3 433	0.70694 $\pm$ 5 380	0.70691 $\pm$ 1 372	0.70704 $\pm$ 1 212	0.70694 $\pm$ 3 244	0.00013		0.00005	
PD						0.70716 $\pm$ 1 864				
NL		0.70686 $\pm$ 1 371	0.70710 $\pm$ 4 294	0.70705 $\pm$ 1 372	0.70691 $\pm$ 2 217	0.70688 $\pm$ 3 223	0.00024		0.00011	
NB		0.70707 $\pm$ 2 228	0.70774 $\pm$ 9 8	0.70693 $\pm$ 1 212	0.70880 $\pm$ 7 13	0.70726 $\pm$ 2 10	0.00186	0.00193	0.00045	0.00038
RW						0.71025 $\pm$ 3 3				
RW						0.70997 $\pm$ 4 2				
RW						0.71132 $\pm$ 5 3				
KW				0.70875 $\pm$ 1 151	0.70948 $\pm$ 1 194					

The maximum difference ($^{87}\text{Sr}/^{86}\text{Sr}$ -range) and the standard deviation (SD) among the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the three aquifers over the five seasons show the isotopic constancy ($<0.00001 =$ good) within wells and stations; (range and standard deviation are only shown if at least four aquifer values are available).

Sr concentrations in ppb; 2σ -values $\times 10^{-5}$; SD standard deviation; waters: *GW* mixture of aquifers from the raw water tap, *LW* lake water, *RW* rainwater, *KW* Mae Klong River water; aquifers: *PD* Phra Pradaeng, *NL* Nakhon Luang, *NB* Nonthaburi

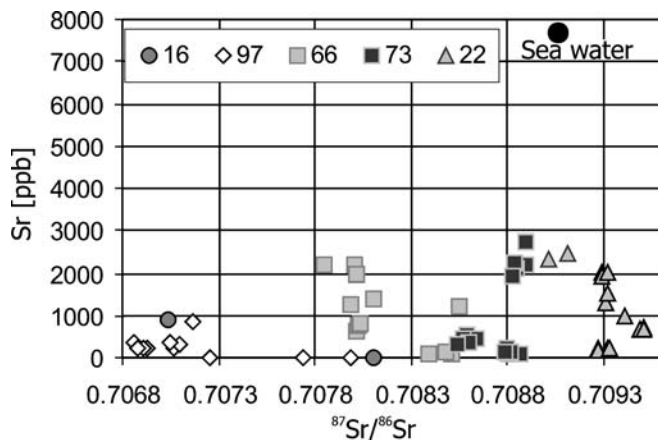


Fig. 8 Distribution of $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr concentrations within the monitoring stations in comparison to the sea-water value

trations (Negr  l et al. 1993, Guillardet et al. 1997). As shown in Fig. 10 for $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Na/Sr and Ca/Sr, respectively, the samples plot on the mixing line between the carbonate and the sea-water end member, confirming the observed trends. Silicates seem to have roughly no influence.

The tracer model

Due to the almost constant $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the three aquifers, the flow of injected water into the aquifers below the Bangkok area could be traced by monitoring the change in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. For former injection tests by Ramnarong (1973), one injection well and six observation wells were drilled into the Bangkok-, the Phra Pradaeng- and the Nakhon Luang aquifers. Two different injection methods were used: a free-flow method without pump and a pressure method with pump. Both methods were successful, the free-flow method with injection rates of $\sim 400 \text{ m}^3/\text{d}$, and the pressure method with $\sim 2,400\text{--}5,600 \text{ m}^3/\text{d}$ under pressures of $1.25\text{--}2.5 \text{ kg/m}^2$. Problems during the tests were mainly caused by clogging and decreasing transmissivities, and also by outbreaks of injected water through the ground surface nearby the recharge well. The specific parameters obtained will be included in the discussion below.

Model basics

For an ideal artificial recharge project, the recharge wells should be located in the path of the groundwater flow within the cone of depression to take advantage of the

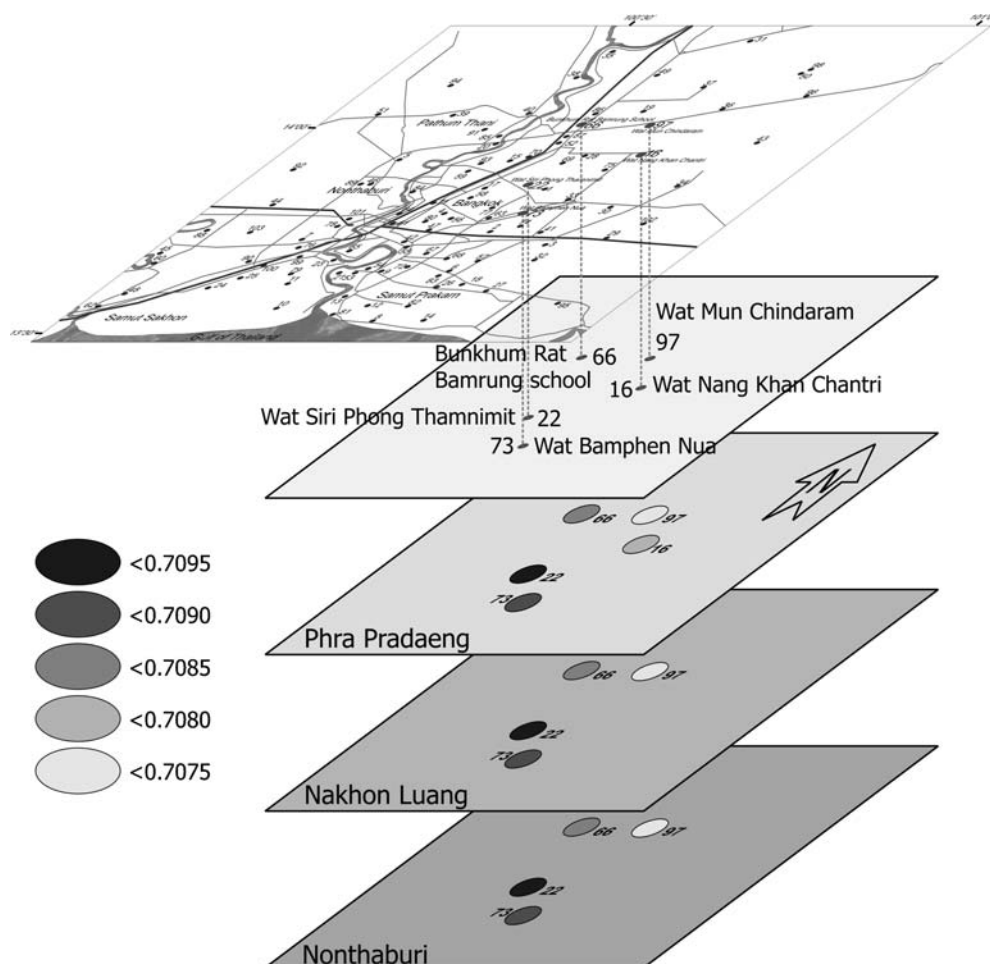


Fig. 9 Distribution of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios within the three aquifers at the five sampling stations; the ratios decrease from SW to NE, with distance from the Gulf of Thailand, and from the cone of hydraulic head depression

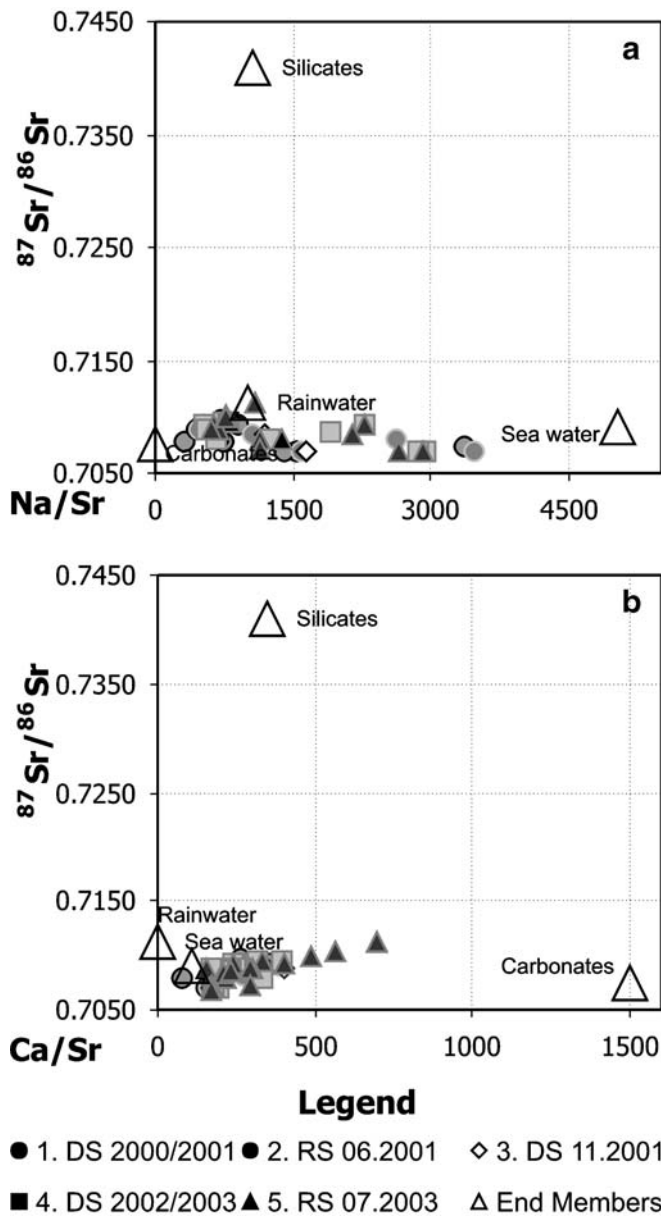


Fig. 10 Comparison of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with **a** Na/Sr and **b** Ca/Sr ratio; the waters plot on the mixing line between carbonates and sea water; end members after Négrel et al. (1993). *DS* is dry season and *RS* is rainy season (see Table 1)

natural drawdown in the direction towards the center of the cone (important for the free-flow method). After installation of each well, the initial hydraulic head has to be measured to provide the pre-injection level h_0 (Schwartz and Zhang 2003). The recovery of the hydraulic head during injection can be estimated by using the Theis recovery method modified in the recent case for confined aquifers and transient flow (Asano 1985); the resulting cone of impression during injection is a mirror image of a cone of depression caused during withdrawal of the same amount that is injected (Fig. 11). Thus, the standard calculation of groundwater flow can also be used for head build-up instead of drawdown. By using a former

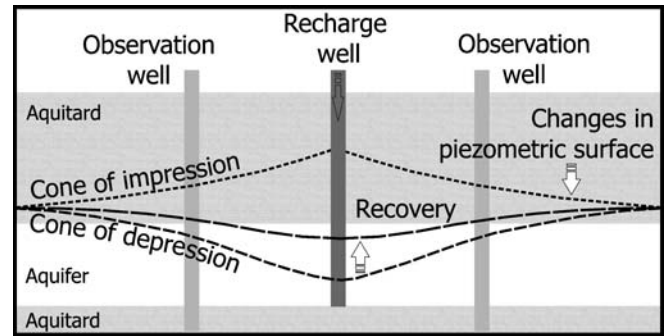


Fig. 11 Simplified cone of depression and cones of impression during conceptual injection of water into an aquifer system

withdrawal well as a recharge well, and under injection rates equal to former withdrawal rates, the recovery in head will be:

$$s = h_0 - h' = \frac{Q}{4\pi T} \times W(u) \quad (1a)$$

with

$$W(u) = \int_u^\infty \frac{e^{-u} du}{u} \quad (1b)$$

and

$$u = \frac{r^2 S}{4Tt} \quad (1c)$$

with h_0 being the initial hydraulic head, h' the recovered head at any time, s the residual recovery, Q the injection rate, T the transmissivity, S the storativity, r the distance from the well, t the time since injection started and $W(u)$ the well function (values for $W(u)$ are summarized in Lohman 1972, p. 16).

In the recent case, the most interesting parameter during injection testing may be the recovery s due to the needed increase in hydraulic head to stop the severe land subsidence. The transmissivities of the relevant aquifers are shown in Table 2.

The injection model

In an idealized area-wide network of recharge- and observation wells that covers the whole metropolitan area,

Table 2 Transmissivity T of the relevant aquifers of the Thon Buri sedimentary basin beneath Bangkok (Ramnarong and Buapeng 1992a)

Aquifers	Transmissivity (m^2/d)
Bangkok	3,950
Phra Pradaeng	1,200–4,104
Nakhon Luang	1,200–4,104
Nonthaburi	3,730
Sam Khok	4,992
Phaya Thai	6,000

the recharge wells should be drilled down into the Nakhon Luang aquifer to the same depth as the former withdrawal wells. The general groundwater flow direction to the coast is negligible for the calculations of the cones of impression if the location of the injection site is within the cone of depression.

The potential increase in hydraulic head will be exemplarily calculated for the specific properties of the Nakhon Luang aquifer. The cone diameter is ~ 500 km. Also, the parameters for the injection method have to be taken into account to get realistic values. Some representative values for transmissivity, storativity and injection rates may be $T=3,000$ m²/d, $S=1\times 10^{-4}$ and $Q=3,600$ m³/d (150 m³/h). Assuming these conditions, the effective increase of the hydraulic head (s) at station 97 after 1, 10 and 100 years of pumped injection is about 0.00049, 0.46 and 224 cm, respectively, for one recharge well. Since s for multiple recharge wells is the sum of s of the individual ones, it would need about 218 recharge wells operating for 10 years under constant conditions to fill up the 40 m of hydraulic head depression by pumping a total of 28,645,200 km³ of water into the ground.

These calculations are inaccurate because several aspects would diminish the recovery: (1) the injected pumping rate decreases with ongoing injection due to the non-linear recovery, (2) the aquifer could be clogged, (3) the spatial extension of the cone is simplified and thus the volume might be different, (4) the necessary amount of surface water can not be cleaned quickly enough, and (5) the relaxation of the land surface to the initial elevation above sea level is not realistic due to the high extra load upon the ground by the city. To get an increase in hydraulic head in a depleted aquifer, this aquifer must be interconnected to the aquifer to which injection takes place. If only the Bangkok aquifer is used for injection, it needs further hydraulic testing to determine whether there is enough interconnection or not; additionally, the recovery in hydraulic head in a depleted aquifer will take longer.

The tracer model

Using the results of the injection model, the tracer properties of $^{87}\text{Sr}/^{86}\text{Sr}$ can be tested for each station and aquifer. The station used for this simplified tracer model is 97, Nakhon Luang aquifer, due to the constant and low background $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7070, which is appreciably different to the sea water ratio of 0.70907.

In this case, a homogeneous mixture of aquifer water and injected water is assumed. In natural groundwater bodies, such mixing is not realistic due to laminar flow of the injected water within the aquifer. The progression front is not vertical and thus shows a dispersive recovery because the aquifer may contain pockets/layers of material with different properties and thus different porosities and permeabilities at different depths. To get a homogeneous mixture of aquifer and injected water, the aquifer material has to be equally heterogeneous throughout the aquifer, there should be no restriction on injection/recovery time

(i.e. the time needed for injection and recovery may be different), and there should be no one-dimensional flow. In case of a better homogeneity of the aquifer material, the front of the injected water can be monitored at the withdrawal well with progressive time during or after the injection: the withdrawn water is a mixture of aquifer water and more and more injected water, due to the dispersive flow in different layers with different velocities.

The mean pre-mixing $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of groundwater in the selected Nakhon Luang aquifer at station 97 is 0.7070 (0.70686–0.70710), and the mean Sr concentration is 295 ppb (217–372). The following considerations are given to the model results for the aquifer and injected water mixture when only one recharge well is used. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios monitored during the mixing process may also be used to track the recovery front while the cone is “filled up”. The tracer properties of the Sr isotopes will be tested by using the results of the injection model to calculate the amount of Sr which is needed to change the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio at a monitoring well.

The pore volume of the Nakhon Luang aquifer has to be calculated to determine the volume of water contained within the aquifer. The Nakhon Luang aquifer has a thickness of at least 50 m and a porosity of sand and gravel of 20%. An exemplarily designed cylinder of 500 m radius and a height of 50 m, placed around one recharge well, has a pore volume of 7.9×10^6 m³. If this pore volume is taken as the water volume, and the concentration of Sr is 295 ppb (which equals 0.0000295%), the total amount of Sr in the cylinder of the resident aquifer will be 2,320 kg.

The amount of Sr being injected into this same well can be calculated by using the previous calculations for the model, i.e. 1,314,000 m³ ($= 365 \text{ d} \times 3600 \text{ m}^3/\text{d}$) of injected water, equivalent to a water level rise in this well of 96 cm.

Mae Klong River water may be a realistic fresh-water source for the model. Hence, the injected water may have an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7164 and a Sr concentration of 657 ppb (Palmer and Edmond 1989). The Sr amount would be 860 kg. A homogeneous mixture of aquifer water (2,320 kg of Sr) and injected river water (860 kg of Sr) would lead to an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7095, which is a significant change of $\sim 0.36\%$ in comparison to the aquifer water ratio of 0.7070. If the aquifer water is affected by sea-water intrusion, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the aquifer water is 0.7090 and the Sr concentration about 2,000 ppb and the change is only $\sim 0.05\%$. In this case, the change is not as great. It could be increased by using higher injection pumping rates and longer injection periods, but the higher the Sr concentration of the groundwater, the more unrealistic are the conditions that are necessary to trace the change in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios after injection.

Conclusions

The land subsidence in the Bangkok area is the physical response to the over-exploitation of the aquifers for public

supply, industrial and private water use in the Bangkok metropolis. To stop the further decline in hydraulic head (up to 40 m in the Thon Buri Basin), an immediate cessation of groundwater withdrawal is proposed.

The significant influence of the sea water that intrudes into the shallow aquifers as a consequence of the decline in hydraulic head complicates the interpretation of the major element and Sr data. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are shown to be spatially influenced by sea-water intrusion, which decreases with increasing distance from the sea (Figs. 8 and 9). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the aquifers at each station have been relatively constant over the 3 years of monitoring. This observation is the basis for tracing the flow paths of injected water during an artificial recharge project, which could be realized in the future. If the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and the Sr concentrations in the resulting mixed aquifer water are significantly lower than the properties of the injected water, the changes resulting from injection can be traced. With increasing influence of sea water, tracing the changes becomes more complicated due to increasing Sr concentrations.

Independent from a planned injection project, the tracer properties of Sr isotopes can also be useful for the government. Sooner or later, the source of water for public use will need to be changed from groundwater to surface water. In this case, the isotopic fingerprints of both groundwater and surface water can be easily used to track illegal groundwater extraction and, with subsequent benefits in respect of land subsidence, this could help to speed up the total shutdown of withdrawal and the re-equilibrium of the groundwater body below the Bangkok area.

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References

- AIT, DMR (1982) Groundwater resources in Bangkok area: development and management study. Comprehensive report 1978–1982, No. 1982–001, National Environmental Board of Thailand, Bangkok
- Albarède F, Michard A, Minster JF, Michard G (1981) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in hydrothermal waters and deposits from the East Pacific Rise at 21°N. *Earth Pla Sci Lett* 55:229–236
- Appelo CAJ, Postma D (1999) *Geochemistry, groundwater and pollution*. Balkema, Rotterdam
- Armstrong SC, Sturchio NC, Hendry MJ (1998) Strontium isotopic evidence on the chemical evolution of pore waters in Milk Aquifer, Alberta, Canada. *Appl Geochem* 13:463–475
- Asano T (1985) Artificial recharge of groundwater. Butterworth Publishers, Stoneham, UK
- Back W (1961) Techniques for mapping of hydrochemical facies. US Geol Surv Prof Paper 424-D:380–382
- Brass GW (1976) The variation of the marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratio during Phanerozoic time: interpretation using a flux model. *Geochim Cosmochim Acta* 40:721–730
- Buapeng S, Lorphensri O (1999) Records of groundwater and land subsidence; monitoring stations in Bangkok and adjacent provinces. Mitigation of groundwater crisis and land subsidence in Bangkok project (MGL project), Technical Report 1, Department of Mineral Resources, Ministry of Industry, Bangkok
- Bullen TD, Krabbenhoft DP, Kendall C (1996) Kinetic and mineralogic controls on the evolution of groundwater chemistry and $^{87}\text{Sr}/^{86}\text{Sr}$ in a sandy silicate aquifer, northern Wisconsin, USA. *Geochim Cosmochim Acta* 60:1807–1821
- Bullen TD, White AF, Blum AE, Harden J, Schulz MS (1997) Chemical weathering of a soil chronosequence on granitoid alluvium: II. mineralogic and isotopic constraints on the behaviour of strontium. *Geochim Cosmochim Acta* 61-2:291–306
- Burke WH, Denison RE, Hetherington EA, Koepnick RB, Nelson HF, Otto JB (1982) Variation of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ throughout Phanerozoic time. *Geology* 10:516–519
- Chaodumrong P, Chaimanee Y (2002) Tertiary sediment basins in Thailand. *Symp Geol Thailand* 156–169
- DMR (1994) Hydrographs of piezometric levels of groundwater in Bangkok and adjacent provinces, Report no. 2. In: Mitigation of groundwater crisis and subsidence in Bangkok project (MGL Project). Department of Mineral Resources, Ministry of Industry, Bangkok
- Durum WH, Haffty J (1963) Implications of the minor element content of some major streams of the world. *Geochim Cosmochim Acta* 27:1–11
- Elderfield H, Gieskes JM (1982) Sr isotopes in interstitial waters of marine sediments from deep sea drilling project cores. *Nature* 300:493–497
- Faure G (1986) *Principles of isotope geology*, 2nd edn. Wiley, New York
- Graustein WC, Armstrong RL (1983) The use of strontium-87/strontium-86 ratios to measure atmospheric transport into forested watersheds. *Science* 219:289–292
- Guillardet J, Dupré B, Allègre CJ, Nègre P (1997) Chemical and physical denudation in the Amazon River Basin. *Chem Geol* 142:141–173
- Hoffman AW, Hart SR (1978) An assessment of local and regional isotopic equilibrium in the mantle. *Earth Pla Sci Lett* 38:95–116
- Holland HD (1978) *The chemistry of the atmosphere and oceans*. Wiley, New York
- Johnson EE (ed) (1966) *Ground water and wells: a reference book for the water-well industry*. E E Johnson Inc., Sugar Land, Texas, USA
- Katz B, Bullen TD (1996) The combined use of $^{87}\text{Sr}/^{86}\text{Sr}$ and carbon and water isotopes to study the hydrochemical interaction between groundwater and lakewater in mantled karst. *Geochim Cosmochim Acta* 60:5075–5087
- Lloyd JW, Heathcote JA (1985) *Natural inorganic hydrochemistry in relation to groundwater: an introduction*. Oxford University Press, New York
- Lohman SW (1972) Ground-water hydraulics. U S Geol Surv Prof Paper 708:1–70
- Martin JM, Meybeck M (1979) Elemental mass-balance of material carried by major world rivers. *Mar Chem* 7:173–206
- Matthess G (1994) *Lehrbuch der hydrogeologie Bd 2: die beschaffenheit des grundwassers* [Textbook of hydrogeology vol 2: the nature of groundwater]. Borntraeger, Stuttgart
- McNutt RH, Frape SK, Fritz P, Jones MG, MacDonald IM (1990) The $^{87}\text{Sr}/^{86}\text{Sr}$ values of Canadian Shield brines and fracture minerals with applications to groundwater mixing, fracture history, and geochronology. *Geochim Cosmochim Acta* 54:205–215
- Nègre P (1999) Geochemical study of a granitic area, the Margeride Mountains, France: chemical element behavior and $^{87}\text{Sr}/^{86}\text{Sr}$ constrains. *Aquatic Geochem* 5:125–165
- Nègre P, Allègre CJ, Dupré B, Lewin E (1993) Erosion sources determined by inversion of major and trace element ratios in

- river water: the Congo Basin case. *Earth Pla Sci Lett* 120:59–76
- Palmer MR, Edmond JM (1989) The strontium isotope budget of the modern ocean. *Earth Pla Sci Letters* 92:11–26
- Peterman ZE, Wallin B (1999) Synopsis of strontium isotope variations in groundwater at Äspö, southern Sweden. *Applied Geochem* 14:939–951
- Phiancharoen C (1972) Ground water of Bangkok. Ground Water open file Report, Ground Water division, Department of Mineral Resources, Bangkok
- Phiancharoen C, Chuamthaisong C (1976) Ground water of Bangkok Metropolis, Thailand. *Int Hydrogeol Conf Hydrogeol of Great Sed Basins*, Hungarian Geological Institute/UNESCO, Budapest
- Phien-wej N, Nutalaya P, Sophonsakulrat W (1989) Current land subsidence of Bangkok and contemplated remedial measures. *Int Symp Land Subsidence*, Asian Institute of Technology, Bangkok, pp 311–321
- Piper AM (1944) A graphic procedure in the geochemical interpretation of water analysis. *Trans Am Geophys Union* 25:914–923
- Ramnarong V (1973) Injection of flood water into an underground reservoir. Ground Water Division, Department of Mineral Resources, Bangkok
- Ramnarong V, Buapeng S (1992a) Groundwater resources of Bangkok and its vicinity: impact and management. In: *Proc National Conf Geol Res Thailand: Potential for Future Development*. Department of Mineral Resources, Bangkok, pp 172–184
- Ramnarong V, Buapeng S (1992b) Saltwater intrusion and land subsidence due to over exploitation of groundwater in Bangkok. *Int Geol Congr Abstr* 29:897
- Saito Y, Tanabe S, Sato Y, Suzuki Y (2002) Holocene evolution of the Lower Central Plain of Thailand. *Symp Geol Thailand, Bangkok*, pp 196–200
- Sanford WE, Buapeng S (1996) Assessment of a groundwater flow model of the Bangkok Basin, Thailand, using carbon-14-based ages and paleohydrology. *Hydrogeol J* 4(4):26–40
- Schwartz FW, Zhang H (2003) *Fundamentals of ground water*. Wiley, New York
- Sinsakul S (2000) Late quaternary geology of the Lower Central Plain, Thailand. *J Asian Earth Sci* 18:415–426
- Tadolini T, Tulipano L (1991) The evolution of fresh-water/salt-water equilibrium in connection with withdrawals from the coastal carbonate and karstic aquifer of the Salentine Peninsula (southern Italy). In: De Breuck W (ed) *Hydrogeology of salt water intrusion*. *Int Contr Hydrol* 11:95–111
- Wadleigh MA, Veizer J, Brooks C (1985) Strontium and its isotopes in Canadian rivers: fluxes and global implications. *Geochim Cosmochim Acta* 49:1727–1736
- Wedepohl KH (1978) *Handbook of geochemistry II-4*. Springer, Berlin
- Wiegand B, Dietzel M, Bielert U, Groth P, Hansen BT (2001) $^{87}\text{Sr}/^{86}\text{Sr}$ -verhältnisse als tracer für geochemische prozesse in einem lockergesteinsaquifer (Liebenau, NW-Deutschland) [$^{87}\text{Sr}/^{86}\text{Sr}$ -ratios as tracer for geochemical processes in a sandy silicate aquifer (Liebenau, NW-Germany)]. *Acta Hydrochim Hydrobiol* 29:139–152