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## Fluctuation of NO<sub>3</sub>-N in groundwater of the reservoir of the Sunagawa Subsurface Dam, Miyako Island, Japan

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**Abstract** The Japanese government started to construct two subsurface dams on Miyako Island in 1988, and the project was completed in 2001. Before the construction of the dams, the NO<sub>3</sub>-N concentration of groundwater on the island was about 10 mg/l, the upper limit for drinking water in Japan, owing to the application of fertilizer to sugarcane fields. Predicting the effect of these subsurface dams on the groundwater environment was difficult because they were probably the first mega-subsurface dams in the world. We measured the NO<sub>3</sub>-N concentration in the groundwater at observation wells before and after construction of the Sunagawa Dam and after the groundwater began to be used. We also measured the NO<sub>3</sub>-N concentration monthly at a typical observation well in the catchment over a period 14 years to evaluate the environmental impact of construction of the dam. The highest NO<sub>3</sub>-N concentrations were downstream before completion of the subsurface dam, and a high NO<sub>3</sub>-N concentration zone remained around the cut-off wall after its completion, but this high-concentration zone disappeared and the distribution of NO<sub>3</sub>-N became uniform after pumping of the groundwater began. Overall, the NO<sub>3</sub>-N concentration decreased gradually. These results show that the groundwater quality did not deteriorate as a result of the construction of the Sunagawa Subsurface Dam.

**Keywords** Mega-subsurface dam · <sup>3</sup>H · Limestone · Fertilizer

### Introduction

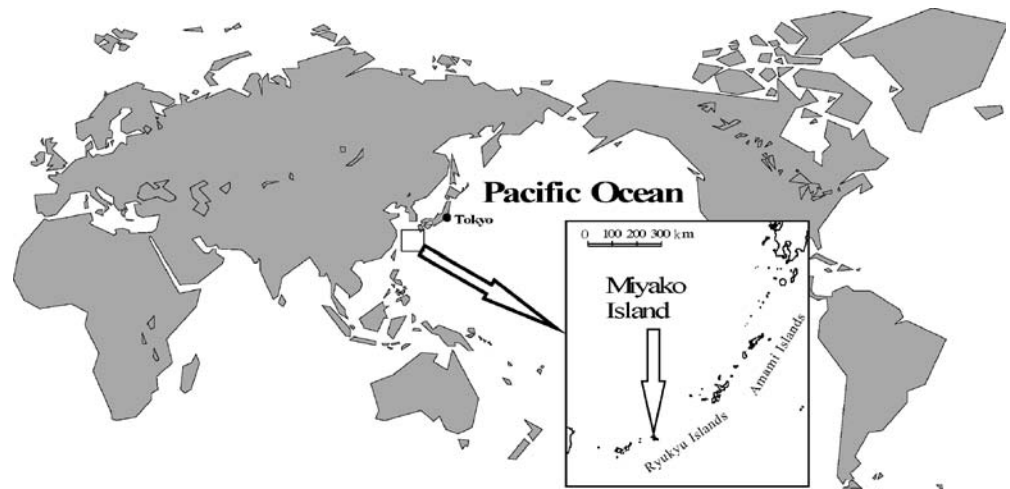
A subsurface dam stores groundwater in the pores of strata and makes sustainable water use possible. Subsurface dams able to store 10<sup>3</sup>–10<sup>4</sup> m<sup>3</sup> of groundwater have been con-

structed previously using available technology and put to practical use in dry regions in Africa, India, China, and elsewhere (Hanson and Nilsson 1986)

Recently, however, a new civil engineering technology called the mixed-in-place slurry-wall method has made it possible to construct subsurface dams able to store 1 million m<sup>3</sup> or more of groundwater (mega-subsurface dams) in locations such as in the Ryukyu and Amami Islands, southwest Japan, where geological and hydrological conditions are suitable (Nagata et al. 1993). These islands consist of highly permeable Quaternary Ryukyu limestone. The Japanese government started to construct the first mega-subsurface dam, the Sunagawa Subsurface Dam, on Miyako Island in 1988. Construction was completed in 1993, and the groundwater reservoir became fully recharged in 1995. Since 2001, a large amount of groundwater has been pumped up to use for irrigation from more than 100 tube wells.

The concentration of NO<sub>3</sub>-N in the groundwater on the island was about 5 mg/l in 1975, but it subsequently increased because of the application of fertilizer to sugarcane fields (Kondo et al. 1997). Before the construction of the subsurface dam began, the concentration of NO<sub>3</sub>-N in the groundwater had reached about 10 mg/l, which is the upper limit for drinking water in Japan in 1988. A subsurface dam drastically changes the groundwater level and groundwater flow from the natural condition. Groundwater quality, especially nitrate contamination and possible changes in nitrate levels caused by the subsurface dam, is one of the most important concerns of the people of Miyako Island because groundwater is the only water source on the island. Therefore, they requested that the effect of the National Irrigation Project and of the construction of mega-subsurface dams be evaluated and that changes in the NO<sub>3</sub>-N concentration in groundwater be predicted. However, it was difficult to predict the effect that these mega-subsurface dams would have on the groundwater environment because these mega-subsurface dams are unique; the natural groundwater flow system had not been altered to this extent anywhere in the world previously (Imaizumi et al. 2002).

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**Fig. 1** Map of the study area

We evaluated the effect of the Sunagawa mega-subsurface dam on nitrogen contamination of the groundwater on Miyako Island by monitoring  $\text{NO}_3\text{-N}$  at observation wells from the planning stage through the period of dam construction, and after the stored groundwater began to be utilized.

### Geological and hydrogeological setting

The Ryukyu Islands, which include Miyako Island, are distributed in an arc from south of Kyushu to Taiwan (Fig. 1). The Ryukyu Trench, with a maximum water depth of 7000 m or more, east of the Ryukyu Islands is a subduction zone, where the Philippine Sea plate is being subducted beneath the Eurasian plate. Because of their location in this tectonically active region, the Ryukyu Islands are being uplifted, and several levels of marine terraces characterize the islands. A reef-facies deposit called the Ryukyu limestone is an uplifted Quaternary limestone found throughout the Ryukyu Islands (Hori and Kayane 2000).

Miyako Island, which is located about 2000 km southwest of Tokyo, is in the subtropical zone; the annual average of temperature is  $23^\circ\text{C}$ , of humidity 80%, and of precipitation 2200 mm (Fig. 1). Topographically, it is a relatively flat plateau, and its highest point is 113 m above mean sea level (a.s.l.). About 57% of the total land area of  $158\text{ km}^2$  is used for agriculture, and 14% is forested. Field crops account for 82% and animal husbandry products for 18% of agricultural production. Sugarcane and tobacco are the main field crops (JGRC 2001). Both rainfed and irrigated agricultural systems were used before construction of the subsurface dams. This island is subject to drought in years when few typhoons occur because most precipitation is brought by sporadically occurring typhoons.

The island geology consists of the highly permeable Quaternary Ryukyu limestone group overlying basement mudstone of the Tertiary Shimajiri group (Fig. 2). The limestone is covered with a lateritic clay soil with a thickness of 0.5–1 m. The Ohnokoshi clay, which is 0–10 m thick, is found in depressions on the Ryukyu limestone.

This clay has been reworked from a lateritic clay soil developed in the basement mudstone.

The Shimajiri group, which is the hydrogeological basement, is estimated to be at least 2000 m thick, and its hydraulic conductivity is less than  $1.0 \times 10^{-7}$  m/s (JGRC 2001). The average hydraulic conductivity of the Ryukyu limestone is  $3.54 \times 10^{-3}$  m/s, and its effective porosity is about 10% (Imaizumi et al. 1988). Good aquifers are common in the Ryukyu limestone, but where the lateritic or Ohnokoshi clays have flowed into the pores of the limestone, its permeability is decreased (Ishida et al. 2003). In the catchment area of the subsurface dams the Ryukyu limestone is 20–50 m thick.

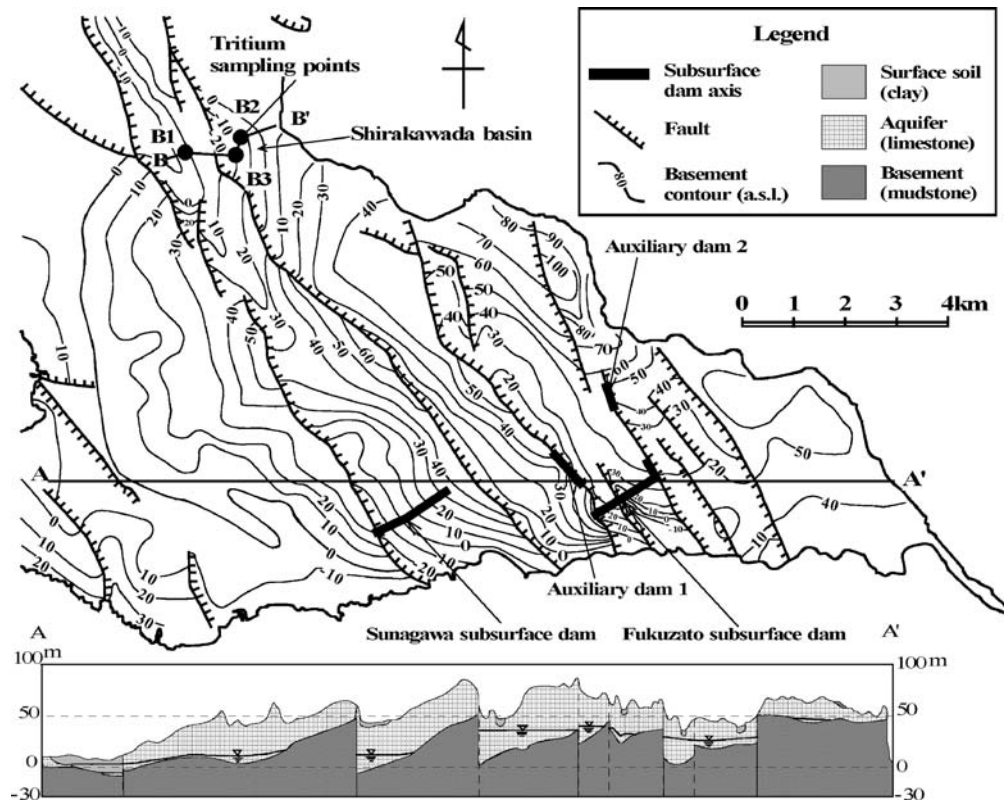
Miyako Island is divided into 23 catchments by the many faults, which are oriented from northwest to southeast, distributed throughout the island (Okinawa General Bureau 1982). The southern part of island exhibits a cuesta topography inclined toward the west (Fig. 2). The fracture zone has not developed around these faults, which are impermeable due to diagenesis. The basement topography has several underground valley-shaped structures between the faults; these valleys are suitable sites for subsurface dam construction (Ishida et al. 2003).

The Shirakawada catchment differs from the catchments in the southern part of the island (Fig. 2). The groundwater basin in the Shirakawada area resembles half of a bowl that is bounded on the west by a northwest–southeast-trending fault. Groundwater stored in the basin flows out at its northeastern edge as the Shirakawada springs.

### National irrigation project

In 1988, as part of the National Irrigation Project, the Japanese government proposed the construction of two subsurface dams, the Sunagawa and Fukuzato dams, on Miyako Island to develop the groundwater resources of the island for agriculture. The total capacity of these two dams is about  $20,000,000\text{ m}^3$ . Table 1 shows the specifications of the two subsurface dams. Two auxiliary dams to prevent

**Fig. 2** Geological section and basement contour map of the study area



leakage of groundwater over the low basement ridge were constructed as part of the Fukuzato Dam Project. Construction began on the Sunagawa Subsurface Dam in 1988, it was completed in 1993, and the groundwater reservoir became fully recharged in 1995. The construction of the Fukuzato Subsurface Dam started in 1994, was completed in 1996, and the reservoir was fully recharged in 1998.

The cut-off walls of the subsurface dams were built with the mixed-in-place slurry-wall method (Ishida et al. 2003). The groundwater is pumped up from 147 tube wells and then stored in farm ponds (water tanks), which supply the pipeline system that serves the entire island.

With the completion of the project in 2001, groundwater from the subsurface dams began to be used for irrigation. Pumpage from the Sunagawa Subsurface Dam was 2.7 million  $m^3$  in 2001, 4.8 million  $m^3$  in 2002, and 5.0 million  $m^3$  in 2003. Groundwater levels remained higher than the full water levels (31 m a.s.l.) during this time period. The construction of the cut-off wall of the Sunagawa dam decreased the thickness of the unsaturated zone in the deepest part of the reservoir area from 38 to 13 m and the hydraulic gradi-

ent from 0.0067 to 0.00012 m/m. In the case of the Fukuzato Dam, the thickness of the unsaturated zone decreased from 26 to 5 m, and the hydraulic gradient decreased from 0.0059 to 0.0026 m/m. The groundwater flow velocities also decreased (Table 2).

## Methods

The underground topography of the basement in the Sunagawa catchment was determined from borehole data from 30 to 40 points/ $km^2$  (Fig. 3). The catchment is bounded on its upstream end by an underground topographic ridge and on either side by faults. The groundwater flows southeast from the ridge, toward the Pacific. Land use in the catchment is for sugarcane fields, except for a small village 1.5 km upstream from the dam. Groundwater samples were collected from seven groundwater observation wells in 1993, from 39 in 2000, and from 40 in 2003. The groundwater collection depth was 5 m below the groundwater table in 1993 and 2000, and 5, 10, 20, and 30 m below the

**Table 1** Specifications of the two subsurface dam systems

	Sunagawa Dam		Fukuzato Dam	
	Main dam		Main dam	Auxiliary dam 1    Auxiliary dam 2
Maximum dam height (m)	50.0		27.0	21.0    6.0
Dam length (m)	1,677		1,790	786    332
Elevation of crest (m a.s.l.)	31.0		46.0	46.0    46.0
Basin area ( $km^2$ )	7.2		12.4	
Total capacity ( $m^3$ )	9,500,000		10,500,000	

**Table 2** Comparisons of hydrogeological conditions before and after construction of the subsurface dams

	Sunagawa Dam		Fukuzato Dam	
	Before construction (1988)	After construction (2001)	Before construction (1988)	After construction (2001)
Groundwater level (m a.s.l.)	7.94	32.17	25.43	46.29
Groundwater level (m below the ground surface)	37.59	13.36	25.52	4.72
Maximum aquifer thickness (m)	26.38	50.6	5.16	25.96
Hydraulic gradient	0.0067	0.00012	0.0059	0.0026
Groundwater flow velocity (m/day)	5.8	0.10	5.1	2.2

groundwater table in 2003. In 2003, the groundwater samples were sequentially collected from shallow depths with a bailer. In addition, long-term monitoring of  $\text{NO}_3\text{-N}$  levels in the groundwater was performed from 1988 to 2001 at observation well 87-SB-9 (SB), located near the Sunagawa subsurface cut-off wall. The groundwater samples from well SB were collected from 5 m below the groundwater table. The collected samples were analyzed for  $\text{NO}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ , and  $\text{NH}_4\text{-N}$  by using ion chromatography (ICA-2000, TOA DKK Ltd., Tokyo, Japan).

Tritium concentrations were measured in the Shirakawada catchment at observation wells B1, B2, and B3 to study the mixing of groundwaters under natural conditions (Fig. 2). In September 1992, groundwater was sampled at 5-m intervals by using a pump at each observation well. Tritium concentrations were analyzed by the method of Kimura (1971) and reported in tritium units (TU). A precision of  $\pm 5\text{--}10\%$  was obtained by routine analysis.

## Results

### $\text{NO}_3\text{-N}$ concentration in groundwater

Most nitrogen occurred as  $\text{NO}_3\text{-N}$ ;  $\text{NO}_2\text{-N}$  and  $\text{NH}_4\text{-N}$  concentrations were negligible. In 1991, 2 years before completion of the Sunagawa Subsurface Dam,  $\text{NO}_3\text{-N}$  ranged from 7.0 to 11.9 mg/l (Fig. 4). The concentration of  $\text{NO}_3\text{-N}$  tended to increase from the upstream to downstream areas, although the data were limited. The concentration of  $\text{NO}_3\text{-N}$  was highest around the dam.

In 2000, 7 years after the completion of the Sunagawa Subsurface Dam,  $\text{NO}_3\text{-N}$  ranged from 2.69 to 9.75 mg/l, with a mean of 6.38 mg/l (Fig. 5). The highest concentrations were at the downstream end of the catchment before completion of the subsurface dam, and the high-concentration zone remained near the cut-off wall after its completion.

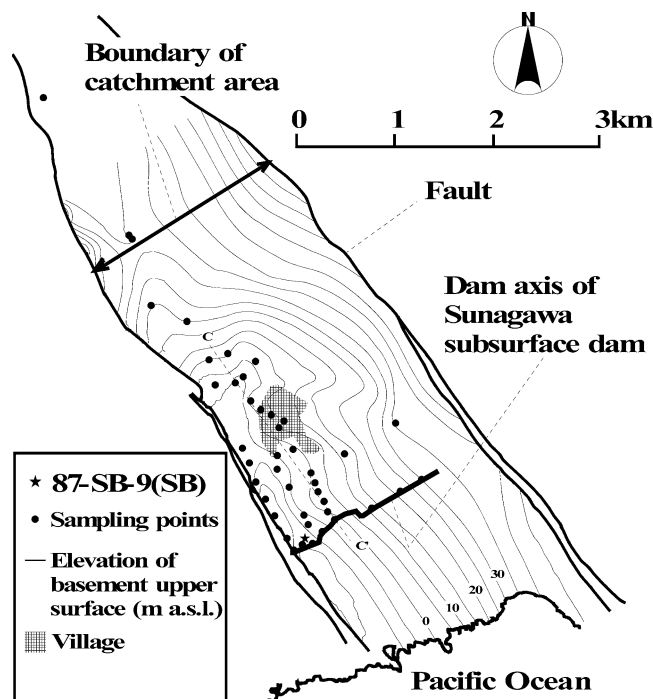


Fig. 3 Sampling points

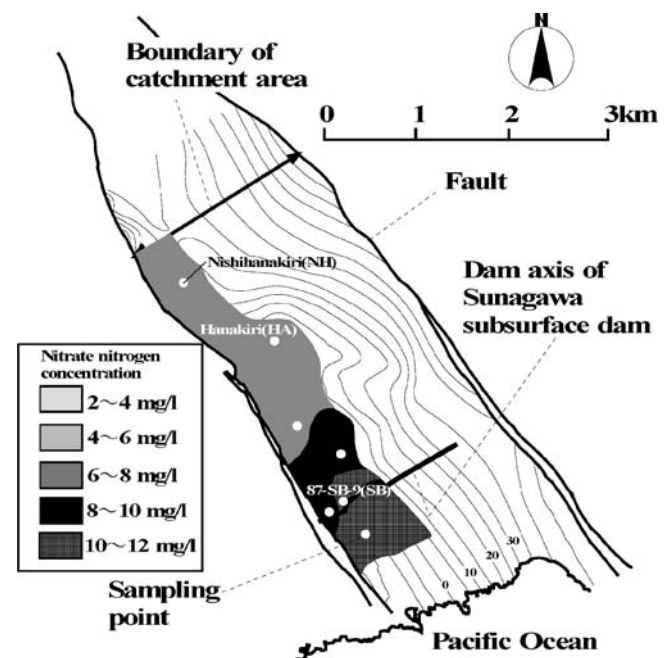


Fig. 4 Distribution map of  $\text{NO}_3\text{-N}$  at 5 m below the groundwater table in 1991

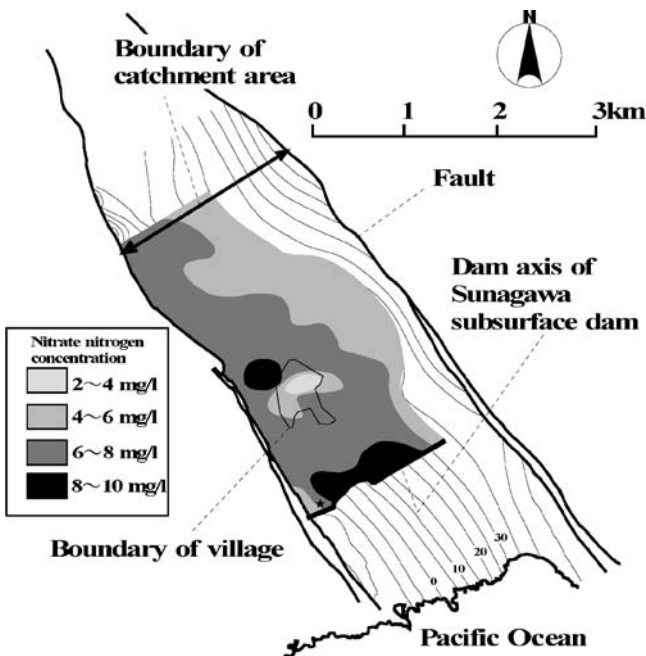


Fig. 5 Distribution map of NO<sub>3</sub>-N at 5 m below the groundwater table in 2000

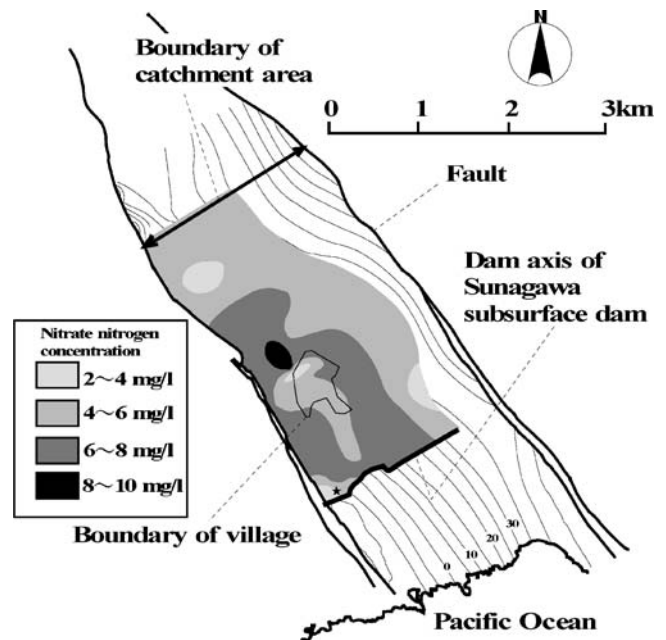


Fig. 6 Distribution map of NO<sub>3</sub>-N at 5 m below the groundwater table in 2003

In 2003, 2 years after the groundwater began to be used for irrigation, NO<sub>3</sub>-N ranged from 2.14 to 8.34 mg/l, with a mean of 5.77 mg/l (Fig. 6). The high-concentration zone near the cut-off wall observed in 2000 had disappeared by 2003.

Near the village, NO<sub>3</sub>-N in 2000 ranged from 2.69 to 6.11 mg/l (mean, 4.76 mg/l), which was lower than that in the surrounding area (Fig. 5). In 2003, NO<sub>3</sub>-N beneath the village was 3.29–6.04 mg/l (mean, 4.71 mg/l), and it was still lower than in the surrounding area (Fig. 6). These results can be explained by assuming that the area with sugarcane fields was relatively less in the village than elsewhere.

Figure 7 shows the NO<sub>3</sub>-N concentrations in 2003 along a transect extending from the Sunagawa cut-off wall to 2000 m upstream. Intake pumps were installed in the tube wells that were distributed from near the cut-off wall to 750 m upstream. From 2001 to 2003, a total volume of 12.5 million m<sup>3</sup> of water was pumped, corresponding to 134% of the total capacity of the subsurface reservoir. The NO<sub>3</sub>-N concentration was comparatively homogeneous with depth, except in a small area near the village. However, the NO<sub>3</sub>-N concentration tended to be low, from

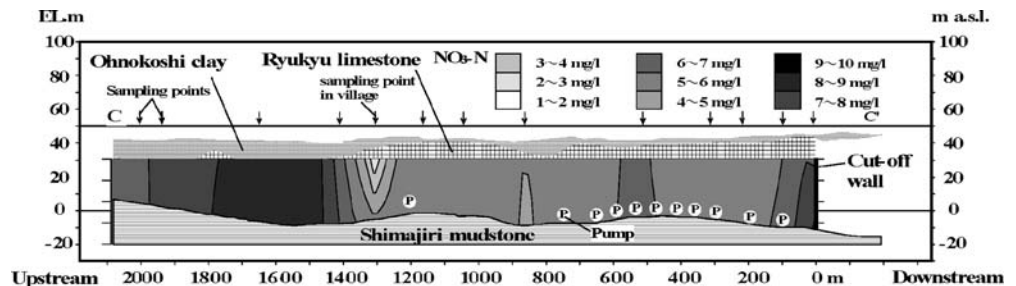
5 to 7 mg/l, in the area where the pumps were installed and the unsaturated zone was in limestone, and it tended to be high, from 8 to 10 mg/l, in the area without pumps and where the unsaturated zone was in the Ohnokoshi clay.

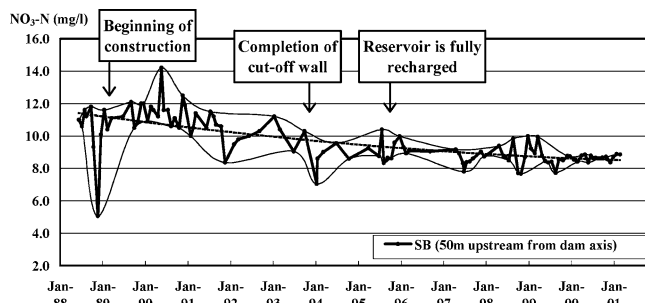
Figure 8 shows fluctuations of the NO<sub>3</sub>-N concentration in the groundwater sampled at observation well SB from 1988 to 2001 (bold line). The monitoring period was divided into three stages to examine the impact of the subsurface dam on the groundwater environment: before completion of the subsurface dam (1988–November 1993), after completion but before the reservoir was fully recharged (December 1993–September 1995), and after the reservoir was fully recharged and recharged water overflowed (October 1995–February 2001).

The pattern of fluctuation of the NO<sub>3</sub>-N concentration can be characterized by a main component (dotted line) and an accessory component (thin lines) (Fig. 8).

The main component describes the overall trend of the NO<sub>3</sub>-N concentration, which decreased from 12.0 mg/l in 1988 to 8.2 mg/l in 2001. This decreasing trend of NO<sub>3</sub>-N has been reported in groundwater of catchments without subsurface dams as well (Tashiro and Takahira 2001); thus,

Fig. 7 Distribution of NO<sub>3</sub>-N in 2003





**Fig. 8** Fluctuation of  $\text{NO}_3\text{-N}$  in groundwater of the catchment of the Sunagawa Subsurface Dam

it is the general trend on Miyako Island. It is notable that this trend was not affected by the construction of the Sunagawa Subsurface Dam, even though long-term monitoring data are available only for the period before and after construction of the dam.

The accessory component is represented by the height of the interval between a line drawn through the concentration maxima and one drawn through the concentration minima (Fig. 8), and it reflects monthly changes in the  $\text{NO}_3\text{-N}$  concentration. This value tended to decrease from the first monitoring stage to the third stage.

Table 3 shows the mean, variance, standard deviation, and relative standard deviation of  $\text{NO}_3\text{-N}$  concentration in groundwater at SB during the three stages. The mean concentration decreased slightly from stage to stage. The variance, standard deviation, and relative standard deviation had decreased by at least one half by the third stage. These trends reflect the effects of recharge from rain, of construction of the subsurface dam, and of full recharge (see Sect. Discussion).

#### Tritium concentrations in the Shirakawada catchment

Tritium ( $^3\text{H}$ ) concentrations in precipitation in Japan have been fairly well established, so the natural tritium concentration in the precipitation was assumed to be about 10 TU (Takashima 1991; Ishida et al. 2005). After nuclear testing in 1952, the tritium concentration in precipitation abruptly increased, reaching its maximum value in 1963. Afterward, it decreased steadily. It has now returned almost to its pre-1952 level. Figure 9 shows the vertical distribution of tritium in groundwater of the Shirakawada catchment in 1992. The  $^3\text{H}$  concentration in B3 and B2 was 5.8–7.7 and 6.8–7.1 TU, respectively.

It must be stressed that there is no correlation between sampling depth and  $^3\text{H}$  concentration. From the viewpoint

of groundwater flow systems, the potential (head) decreases with increasing depth in the recharge area, so the flow is downward, and the head increases with increasing depth in discharge areas, so the flow is upward (Toth 1963). The region between the recharge and discharge areas, where the equipotential lines are vertical or near vertical, is called the region of lateral flow. Tritium concentrations are expected to decrease with depth in the recharge area, and in the discharge area, they are expected to increase with depth. The patterns of change in  $^3\text{H}$  concentrations at B2 and B3 (Fig. 9) suggest that the study area in the Shirakawada catchment is a region of lateral flow.

The average tritium concentration at B2 was 6.65, and that at B3 was 6.83 TU. At B2, the concentration ranged from 6.0 to 7.3 TU, so the precision is  $\pm 10\%$ . Tritium concentrations at B3 ranged from 6.3 to 7.6 TU, if the value of 5.8 TU is excluded, so the precision is also  $\pm 10\%$ . Thus, under natural flow conditions, the groundwater was vertically well mixed.

If groundwater with an initial  $^3\text{H}$  concentration of 6.83 TU flows by piston flow from B3 to B2 and the final  $^3\text{H}$  concentration at B2 is 6.65 TU, then the time required for the groundwater to flow from B3 to B2, a distance of 450 m, can be estimated as 168 days from the equation above. The velocity of groundwater flow was therefore calculated as 2.68 m/day. The hydraulic gradient of this area was about 1/500, the Darcy velocity is  $2.68 \text{ m/day} \times 0.1$  (average porosity) = 0.268 m/day, the hydraulic conductivity is  $0.268 \text{ m/day}/(1/500) = 1.55 \times 10^{-3} \text{ m/s}$ . The average hydraulic conductivity of the Ryukyu limestone is  $3.54 \times 10^{-3} \text{ m/s}$ . Because the estimated value for the velocity of groundwater flow has the same order with the hydraulic conductivity, 168 days is a reasonable estimate for the age.

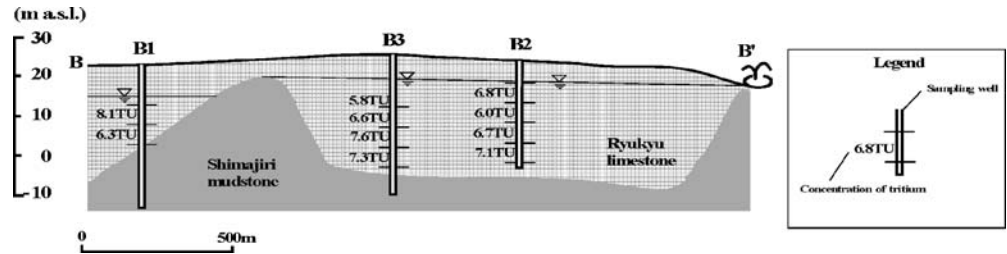
#### Discussion

Tashiro and Takahira (2001) studied the relationship between the fluctuation patterns of  $\text{NO}_3\text{-N}$  in groundwater at 13 wells on Miyako Island and the fluctuation patterns of nitrate loading from fertilizer and animal waste from 1977 to 1999 using commercial fertilizer sales data and agricultural statistics. The  $\text{NO}_3\text{-N}$  concentration curve in groundwater was convex, reaching a maximum in 1987, and the pattern of nitrate loading was similar, but reached the maximum value in 1980. From these data, they concluded that the travel time of  $\text{NO}_3\text{-N}$  from the ground surface to the groundwater table through the unsaturated zone of the limestone was 7 years. Nakanishi (2001)

**Table 3** Fluctuation of  $\text{NO}_3\text{-N}$  in groundwater before and after completion of the cut-off wall (mg/l)

Term	Mean	Variance	Standard deviation	Relative standard deviation
Before completion of the subsurface dam	10.8	1.72	1.31	0.121
After completion but before full recharge	8.82	0.75	0.87	0.0984
After full recharge	8.74	0.22	0.47	0.0547

**Fig. 9** Tritium concentration in groundwater at the Shirakawada basin



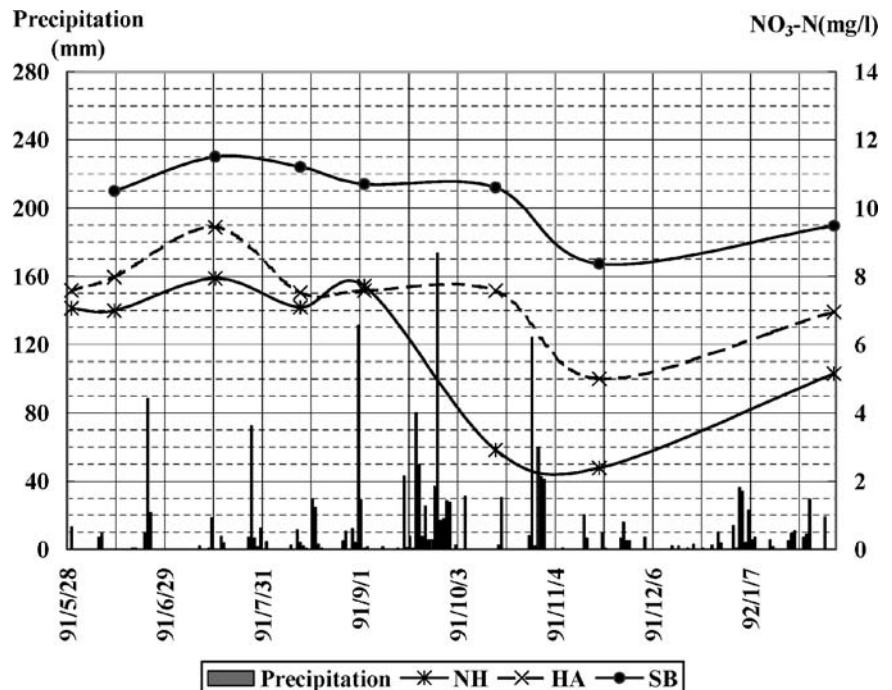
monitored  $\text{NO}_3\text{-N}$  concentrations in groundwater of Miyako Island weekly for more than 5 years and identified two  $\text{NO}_3\text{-N}$  concentration trends: a long-term trend showing a gradual decrease, described by a linear equation with negative slope ( $y = -0.0014x + 52.1$ ), and seasonal fluctuations, with the minimum concentrations observed in September to October. The  $\text{NO}_3\text{-N}$  concentration was negatively correlated with precipitation ( $r^2 = 0.192$ ) with a time lag of 0–1 month. Nakanishi (2001) attributed the seasonal fluctuation in the  $\text{NO}_3\text{-N}$  concentration to the application of chemical fertilizer and its subsequent uptake by plants, because farmers in this area apply chemical fertilizer 2–3 months after the planting of the sugarcane in August. The average age of farmers in this island is 61.8 years, which is very high in Japan. Therefore, to save labor, farmers tend to apply a lot of fertilizer to the first stage of sugarcane planting, though the government is recommending the farmer to give the fertilizer by dividing. These findings suggest that the unsaturated zone of limestone has two porosities: a flow path with a travel time of 7 years and one with a travel time of 0–1 month.

The regional distribution patterns of  $\text{NO}_3\text{-N}$  in the Sunagawa reservoir area varied among the three stages. During the first stage, before completion of the subsurface dam (1988–November 1993),  $\text{NO}_3\text{-N}$  gradually increased

downstream (Fig. 4). During the second stage, after completion of the subsurface dam but before the groundwater in the reservoir was used for irrigation (December 1993–March 2001), the high-concentration zone remained near the cut-off wall (Fig. 5). During the third stage, after irrigation had begun (April 2001–), the high-concentration zone disappeared and an extensive homogeneous area where the  $\text{NO}_3\text{-N}$  concentration was 4–5 mg/l developed in the reservoir area as a result of the pumping of a large volume of groundwater for irrigation (Fig. 6). In cross section, the  $\text{NO}_3\text{-N}$  concentration was homogeneous during the third stage between cut-off wall and 1000 m or more upstream from the cut-off wall, where the intake pumps were installed (Fig. 7).

A big typhoon, No. 19, battered Miyako Island in September 1991. Total precipitation from 15 to 30 September caused by this typhoon was 527 mm. Figure 10 shows the relationship between daily precipitation and fluctuations of  $\text{NO}_3\text{-N}$  concentration from May 1991 to July 1992 at the Nishihanakiri (NH), Hanakiri (HA), and SB observation wells (Fig. 4). NH is upstream, HA is in the middle, and SB is downstream in the catchment area. The decreases in the  $\text{NO}_3\text{-N}$  concentration in groundwater caused by 174 mm of rain falling on 24 September and by 131 mm of rain falling on 31 August 1991 show a response time lag of 0–

**Fig. 10** Relationship between daily precipitation and fluctuations of  $\text{NO}_3\text{-N}$  concentration from May 1991 to July 1992



1.5 month between observation wells. In contrast, 89 mm of rain on 23 June 1991 and 73 mm of rain on 27 July 1991 did not cause decrease so much in the  $\text{NO}_3\text{-N}$  concentration at any of the three observation wells.

Limestone permeability is more heterogeneous than that of noncarbonate rocks because limestone has secondary porosity, caused by enlargement of pores and cracks (created by tectonic movement) by dissolution (karstification), besides the original interstitial porosity between sedimentary grains. Moderately large openings serving as inlets for the infiltration of rain into the unsaturated zone tend to enlarge by solution; in contrast, small openings not connected to the infiltration pathway enlarge only slightly (Legrand and Stringfield 1971). Consequently, the unsaturated zone of limestone has both micropores and macropores.

These observations suggest that the decrease in  $\text{NO}_3\text{-N}$  concentration in groundwater occurs after rainwater from a storm of 100 mm rainfall/day or more passes through the macropores. The presence of macropores has important implications for the rapid movement of solutes and pollutants through soils and rocks composed of chalk or limestone. Beven and Germann (1982) reviewed evidence showing that macropores play an important role in the hydrology of some field soils. Foster and Smith-Carington (1980) identified by-pass flow through macropores (both microfissures and large pores) in chalk from a balance calculation of tritium in the unsaturated zone and suggested that up to 15% of the tritium was transported by the preferential flow of water through macropores. The fraction of water moving in this way in chalk in England has been estimated as 6–15% of total water movement (Smith et al. 1976). This type of flow is currently thought to occur principally during heavy rainstorms. The characteristic size of macropores in chalk has been estimated to be 0.01–0.2 mm. Such voids are unlikely to represent more than 1% of the chalk by volume (Foster and Smith-Carington 1980). Hosotani and Ito (1986) suggested that voids constitute 2% of the Ryukyu limestone by volume on the basis of the water balance calculated with a numerical distributed model that accounted for the macropore system. Peterson et al. (2002) studied the discharge rate of nitrate in a spring discharging from a limestone aquifer in northwest Arkansas. They found that 74% of the nitrate was discharged under base-flow conditions and the remaining 26% was discharged after rapid recharge associated with precipitation storm pulses. Monthly fluctuation of  $\text{NO}_3\text{-N}$  in the long-term record was also related to the dilution of groundwater by storm rains flowing through macropores causing low  $\text{NO}_3\text{-N}$  concentrations. Preferential flow through macropores in Ryukyu limestone on Miyako Island may occur after storms of 100 mm/day or more of rain.

The rates of decrease of  $\text{NO}_3\text{-N}$  at NH, HA, and SB in response to storms of 100 mm/day or more of rain were 5.3, 2.6, and 2.3 mg/l, respectively, and the degree of dilution tended to be lower downstream. In contrast, the thickness of the saturated zone at NH, HA, and SB was 7.06, 11.95, and 16.7 m, respectively, and tended to be larger in downstream. Thus, the degree of dilution is smaller when the buffer volume of groundwater is larger. The decrease in

range of  $\text{NO}_3\text{-N}$  concentration (the accessory component) in response to storm rains from the second to the third stage may be related to the increase in the buffer volume of stored groundwater behind the subsurface dam.

The vertical distribution of  $^3\text{H}$  in the Shirakawada basin shows no correlation between sampling depth and  $^3\text{H}$  concentration in this limestone aquifer. Thus, the groundwater is vertically well mixed under natural groundwater flow conditions. Because recharge water mixed with the laterally flowing groundwater, the  $^3\text{H}$  concentration in the aquifer was homogeneous. Fresh water from rainfall was mixed simultaneously with the upper part of the groundwater body in the saturated zone as it flowed laterally. Groundwater near the groundwater table within a certain area of the aquifer may become homogeneous immediately because of the high permeability of the limestone. This certain area can be defined as the representative volume element for dispersion of  $\text{NO}_3\text{-N}$  under natural flow conditions. Because the average  $^3\text{H}$  concentration at B2 (6.65 TU) is different from that at B3 (6.83 TU), the distance over which such a homogeneous groundwater body extends under natural groundwater flow cannot exceed 450 m in the Shirakawada basin.

In the cross section showing the distribution of  $\text{NO}_3\text{-N}$  during the third stage (Fig. 7), the zone of high concentration around the subsurface cut-off wall present during the second stage has disappeared, and a homogeneous zone with a  $\text{NO}_3\text{-N}$  concentration of 4–5 mg/l extends 1000 m or more upstream from the cut-off wall. The disappearance of the high-concentration zone seems to be closely related to the high pumpage, 134% of the reservoir volume, from the many tube wells arranged in lines paralleling the underground valley. The groundwater stored downstream flowed in the reverse of the natural direction sometimes because the groundwater table was kept at the level of the top of the cut-off wall for 3 years. The cut-off wall and the artificial groundwater flow caused by pumping resulted in the homogeneous distribution of  $\text{NO}_3\text{-N}$ .

Figure 11 shows annual cultivation acreage of sugarcane in Miyako Island and annual average  $\text{NO}_3\text{-N}$  concentration in groundwater at well SB. The cultivation acreage of sugarcane shows the tendency to keep decreasing from 1989 by farmer's aging and the depression of the price of sugarcane, etc. This tendency is corresponding to a decrease in the

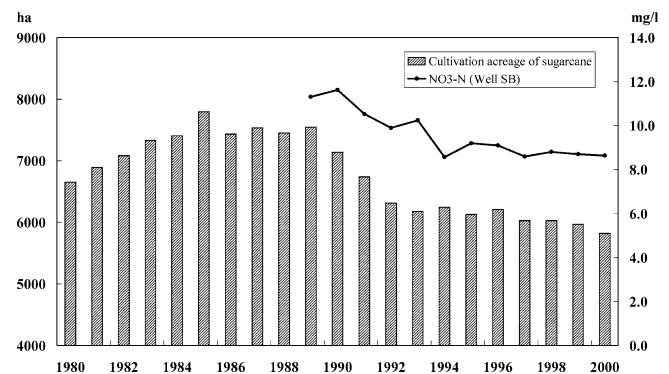
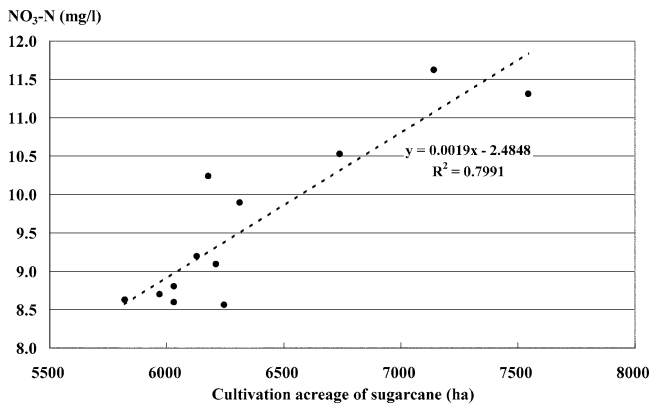


Fig. 11 Annual cultivation acreage of sugarcane in Miyako Island and  $\text{NO}_3\text{-N}$  concentration in groundwater at well SB





**Fig. 12** Relationship between cultivation acreage of sugarcane and NO<sub>3</sub>-N concentration in groundwater at well SB

NO<sub>3</sub>-N concentration in the groundwater. Figure 12 shows relationship between cultivation acreage of sugarcane and NO<sub>3</sub>-N concentration in groundwater at well SB. There is a high, positive correlation between the two, and the correlation coefficient is  $r^2 = 0.80$ . These results show that the reason why the nitrate concentration in the groundwater decreased gradually depended on a decrease in the cultivation acreage of sugarcane. After 1995 when the reservoir became being filled with water, the cultivation acreage of sugarcane and NO<sub>3</sub>-N concentration in the groundwater almost both showed a level off or a little decrease. This shows that the construction of subsurface dam did not influence NO<sub>3</sub>-N concentration in the groundwater so much.

## Conclusions

We studied the impact of a subsurface dam on groundwater flow using NO<sub>3</sub>-N concentration as an indicator of the groundwater environment.

The regional distribution patterns of NO<sub>3</sub>-N in the reservoir area varied among three stages: before completion of the subsurface dam (1988–November 1993), after completion of the subsurface dam and before use of the groundwater for irrigation (December 1993–March 2001), and after irrigation began (April 2001–). During the first stage, the NO<sub>3</sub>-N concentration increased gradually in the downstream direction. During the second stage, there was a high-concentration zone around the cut-off wall. During the third stage, the high-concentration zone disappeared and an extensive homogeneous area with a NO<sub>3</sub>-N concentration of 4–5 mg/l developed in the reservoir area because of large-scale pumping of groundwater for irrigation. This homogeneous zone of NO<sub>3</sub>-N concentration extended 1000 m or more upstream from the cut-off wall, where intake pumps were installed.

The vertical distribution of <sup>3</sup>H in observation wells B2 and B3, which are 450 m apart, showed that groundwater was well mixed under natural lateral groundwater flow conditions. The difference in the average <sup>3</sup>H concentration at B2 (6.65 TU) and B3 (6.83 TU) indicates that the lateral dimension of a homogeneous groundwater body under nat-

ural groundwater flow must not exceed 450 m. The 1000 m length of the homogeneous groundwater body in the reservoir area during the third stage thus indicates that artificial groundwater flow caused by pumping strongly affected the groundwater environment.

Long-term fluctuations in NO<sub>3</sub>-N contained a main component and an accessory component. The main component showed a gradual decrease in the NO<sub>3</sub>-N concentration of 3.2 mg/l over 13 years. A decrease in NO<sub>3</sub>-N concentration harmonized with a decrease in the sugarcane cultivation acreage, and this tendency was similar after having constructed the subsurface dam. This result shows that the construction of subsurface dam did not influence NO<sub>3</sub>-N concentration in the groundwater so much.

The accessory component showed irregular monthly fluctuations in the NO<sub>3</sub>-N concentration. The magnitude of the accessory component became smaller during the second stages.

The NO<sub>3</sub>-N concentration measured at three wells decreased after a rainstorm with 100 mm/day or more of rain, with a delay of 0–1 month. The rainfall, with a low NO<sub>3</sub>-N concentration, rapidly recharged the reservoir through macropores such as fissures or large pores and diluted the stored groundwater having a high concentration of NO<sub>3</sub>-N. The degree of dilution was smaller downstream, indicating that the degree of dilution is smaller when the buffer volume of groundwater is larger. The decrease in the magnitude of the accessory component at the second stage may be related to the increase in the buffer volume of stored groundwater behind the subsurface dam. Our study showed that construction of the subsurface dam and pumping of the stored groundwater for irrigation strongly affected the groundwater environment, including groundwater flow and mixing of waters in the aquifer. The subsurface dam did not cause an increase in the NO<sub>3</sub>-N concentration in the stored groundwater after 3 years of irrigation. NO<sub>3</sub>-N concentrations in the stored groundwater are unlikely to increase in the future because nitrate loading has recently been reduced on Miyako Island. However, the NO<sub>3</sub>-N concentration in the reservoir area should be carefully monitored from now on because of the considerable time required for nitrate to move through the limestone aquifer system.

## References

- Beven K, Germann PP (1982) Macropores and water flow in soils. *Water Resour Res* 18:1311–1325
- Foster SSD, Smith-Carlington A (1980) The interpretation of tritium in the chalk unsaturated zone. *J Hydrol* 46:343–364
- Hanson G, Nilsson A (1986) Ground-water dams for rural-water supplies in developing countries. *Groundwater* 24(4):497–506
- Hori K, Kayane H (2000) Submarine morphology of the island shelf off the middle and south Ryukyu Islands, southwest Japan (in Japanese). *Geograph Rev Jpn* 73A-3:161–181
- Hosotani H, Ito Y (1986) A new hydrographical model for the unconfined groundwater basin (in Japanese). *J Jpn Soc Eng Geol* 27(2):53–60
- Imaizumi M, Maekawa T, Nagata J, Tomita T (1988) Hydrogeological simulation of Miyakojima Island subsurface dam plan (in Japanese). *J JAGH* 30:11–23

- Imaizumi M, Okushima S, Shiono T, Takeuchi M, Komae T (2002) Soil water intrusion into a Ryukyu limestone aquifer in Komesu underground dam basin southern part of Okinawa Island (in Japanese). *Trans JSIDRE* 221:11–23
- Ishida S, Kotoku M, Abe E, Fazal MA, Tsuchihara T, Imaizumi M (2003) Construction of subsurface dams and these impact on the environment. *RMZ Materials and Geoenvironment* 50(1):149–152
- Ishida S, Hara I, Tsuchihara T, Imaizumi M (2005) Evaluation of the drainage effect by drain tunnel in tertiary mudstone landslide area using a neutron moisture logging and environmental isotopes in groundwater (in Japanese). *Landslides* 41(5):467–474
- Japan Green Resources Corporation (JGRC) (2001) Report on an Agricultural Land Conservation Project in the Miyako Region
- Kimura S (1971) Study of groundwater flow by tritium concentration in water (in Japanese). *Bull Natl Res Inst Agric Eng* 9:1–46
- Kondo H, Tase N, Hirata T (1997) Nitrogen isotope ratio of nitrate of groundwater in Miyako Island Okinawa Prefecture (in Japanese). *J JAGH* 39(1):1–15
- Legrand HE, Stringfield VT (1971) Development and distribution of permeability in carbonate aquifers. *Water Resour Res* 7(5):1284–1294
- Nagata S, Enami N, Nagata J, Katho T (1993) Design and construction of cutoff walls for subsurface dams on Amami and Ryukyu Islands in the most southwestern part of Japan. *Hydrogeol Select Papers* 4:229–245
- Nakanishi Y (2001) Correlation between actual fertilizing to sugarcane and nitrate concentration in groundwater of Miyako Island, Okinawa, Japan (in Japanese). *J Soil Sci Plant Nutr* 72:499–504
- Okinawa General Bureau (1982) Hydrogeological map of Miyakojima Island (in Japanese)
- Peterson EW, Davis RK, Brahana JV, Orndorff HA (2002) Movement of nitrate through regolith covered karst terrane, northwest Arkansas. *J Hydrol* 256:35–47
- Smith DB, Downing RA, Monkhouse RA, Otlet RL, Pearson FJ (1976) The age of groundwater in the chalk of the London basin. *Water Resour Res* 12(3):392–404
- Takashima Y (1991) Environmental tritium—Its behavior and utilization (in Japanese). *Radioisotopes* 40:520–530
- Tashiro Y, Takahira K (2001) Long term trend of nitrogen emission and nitrogen concentration of groundwater in Miyako Island, Okinawa (in Japanese). *J JSWE* 24(11):733–738
- Toth J (1963) A theoretical analysis of groundwater flow in small drainage basins. *J Geophys Res* 68(16):4795–4812