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REVIEW
Sustainable Use of Groundwater with Underground Dams

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Abstract

A subsurface dam is a facility that stores groundwater in the pores of strata and uses groundwater in a sustainable way. These dams have many merits that surface dams do not, e.g., land is not submerged to store water and there is no danger of breaching due to natural or manmade disasters. In addition, the surface area can be used in the same way before and after construction of the subsurface dam. Because of these merits, there are many underground dams in the world. This paper reviews the basics about underground dams, the construction of underground dams around the world, and the problems involved in the sustainable use of groundwater. According to a recent review of the construction of underground dams, the scale of underground dam projects has grown. Some problems with underground dams reported in the past, i.e., sedimentation, flooding, collapse, and salination, occurred because of human error, as well as the immaturity and complexity of geological features. In terms of water quality, long-term monitoring was carried out after construction of underground dams on Miyako Island, Japan. To deal with any problems, countries must exchange information gathered from their experiences in constructing underground dams.

Discipline: Agricultural engineering
Additional key words: groundwater, sand storage dam, subsurface dam, water supply

Introduction

An underground dam is a facility that stores groundwater in the pores of strata to enable sustainable use. These dams have many advantages, e.g., unlike a surface dam, land is not submerged to store water and there is no danger of breaching due to natural or manmade disasters. The surface area can be used in the same way both before and after construction of the underground dam. An underground dam allows the development of water resources in regions where the construction of surface dams is difficult due to geological conditions, and where groundwater cannot be used in its current state (low water table, etc.). Underground dams are composed of a cut-off wall to dam the groundwater flow and prevent the intrusion of seawater, as well as facilities (wells, intake shaft, and pumps) that draw up the stored groundwater. Since the utilization of stored groundwater in an underground dam requires pumping, the operating costs are higher than those of a surface dam.

Underground dams that store a few hundred to several million m^3 of groundwater have been previously constructed using available technology, such as the mix-in-place construction method, and put to practical use in dry regions[9]. Recently, the concept of the underground dam has spread, and many underground dams have been constructed. This paper lists recently constructed underground dams around the world and reviews some problems of underground dams, including their environmental impact.

Basic information about underground dams

1. Classification of underground dams

Groundwater runs through a specific hydrologic cycle, so the flow rate varies depending on the geological characteristics of the stratum holding the groundwater, the depth of the stratum, and the permeability and shape of the basement. Generally, shallower groundwater has a higher flow rate. Where groundwater runs at a relatively high rate, the water can be stored by damming the upstream flow with an impermeable wall as is done with rivers[18]. Hanson and Nilsson (1986) divided underground dams into two types[8]:

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(1) subsurface dams constructed below ground level that arrest the flow of a natural aquifer; and (2) sand storage dams that impound water in sediments accumulated by the dam itself (Fig. 1).

Underground dams are also classified according to their purpose, industrial method, and storage type.

Classification by purpose, such as the difference between storage dams and salt water intrusion prevention dams, is important. Storage dams are used to raise the groundwater level where the groundwater table is originally low. Salt water intrusion prevention dams are used to prevent salt water from infiltrating the aquifer from the sea. Figure 2 shows the differences between these two types of dams.

The main construction method for subsurface dams is grouting, but recently other methods have been used for the construction of underground dams. Figure 3 shows a conceptual diagram of the mix-in-place construction method used in Japan.

2. Location requirements

In Japan, the Okinawa General Bureau (1986) summarized the location requirements for the construction of underground dams as follows[18]: (1) There must be an aquifer with permeability efficient enough to collect groundwater, and with a porosity efficient enough to store the necessary groundwater. (2) The stratum (impermeabilities base) should be in the subordinate position and the surroundings in the storage layer.[6] (3) There must be sufficient groundwater recharge to correspond to the amount of water to be stored. Specifically, an underground dam can be constructed in limestone on the basement rock, a plateau composed of volcanic rock with high porosity, coastal plains composed of gravel and sand, an alluvial fan, etc.

Recently, the JGRC (2006) summarized the technical details for the construction of underground dams[10]. For example, the requirements for the site where the underground dam is constructed are as follows: (1) The distribution of geological layers (reservoir layers) must allow for effective porosity and hydraulic conductivity so groundwater can be stored and collected. (2) In the lower part of the reservoir, the basement must be of low permeability, and by closing off a part on top of this basement, efficient storage can sufficiently be expected. (3) The basement surface must be at a depth where construction is possible if the point of the dam axis is established. In addition, cut off is economically possible (construction area for dam extension). (4) There must be a groundwater charging area to match the planned water amount for development. (5) There must be

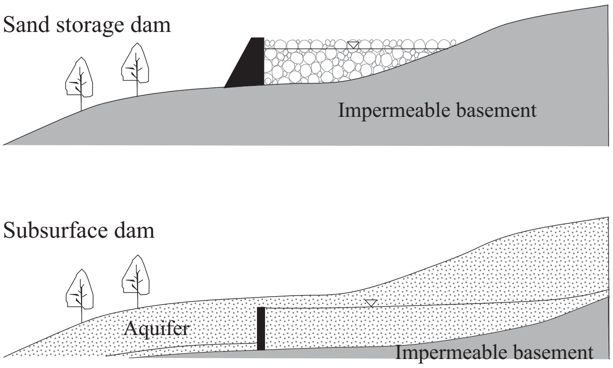


Fig. 1. Sand storage dam and subsurface dam

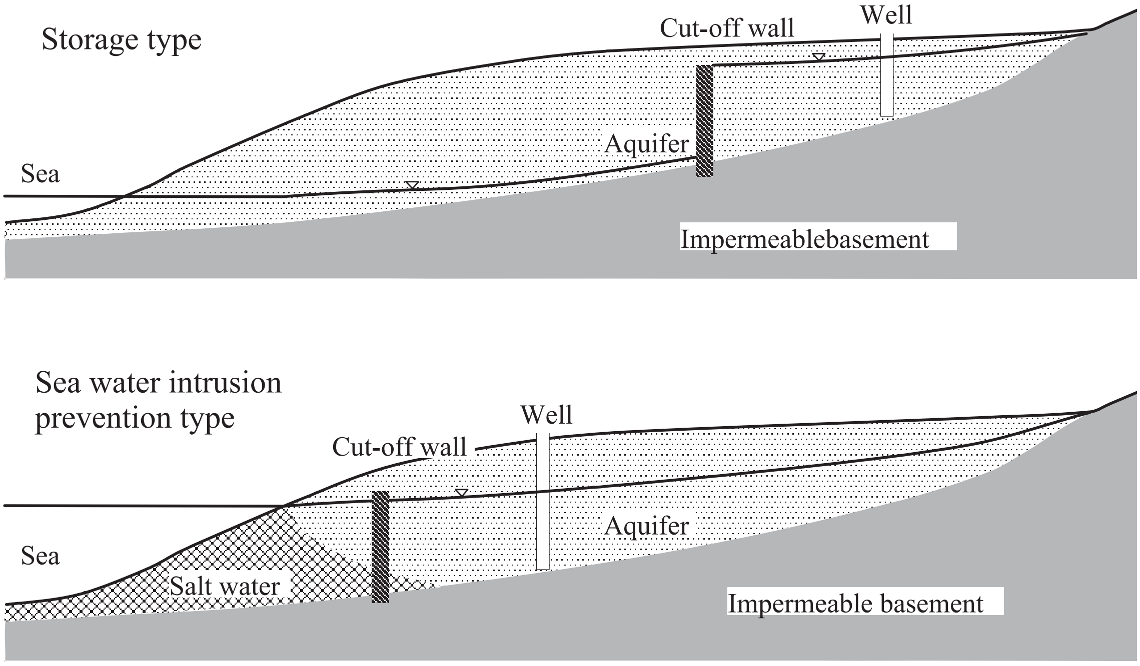


Fig. 2. Geological cross-section and basement contour map of the study area

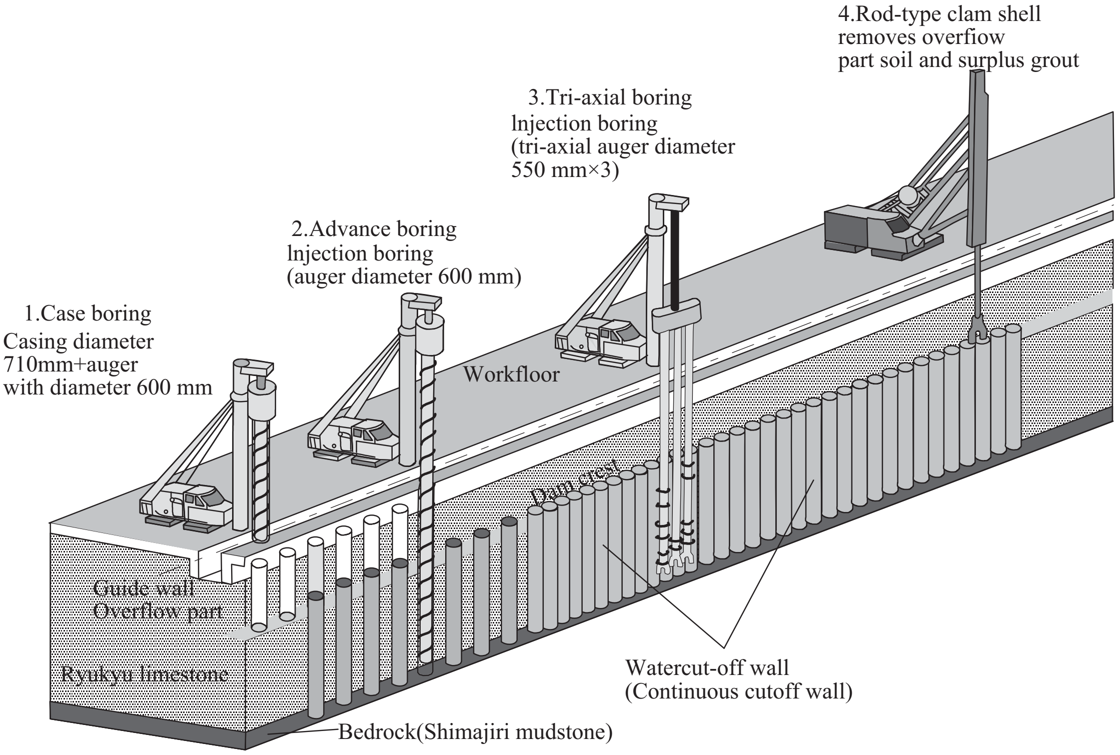


Fig. 3. Conceptual diagram of the mix-in-place construction method (Ishida et.al. 2003 retouched)

little existing use of groundwater. (6) The water quality must be in a range permissible for usage. (7) There must be little impact on the lower catchment area.

3. Development of water resources using underground dams

Water resource development using underground dams is conducted in four steps, namely "basic studies", "planning studies/design", "construction", and "operation and maintenance" (Table 1).

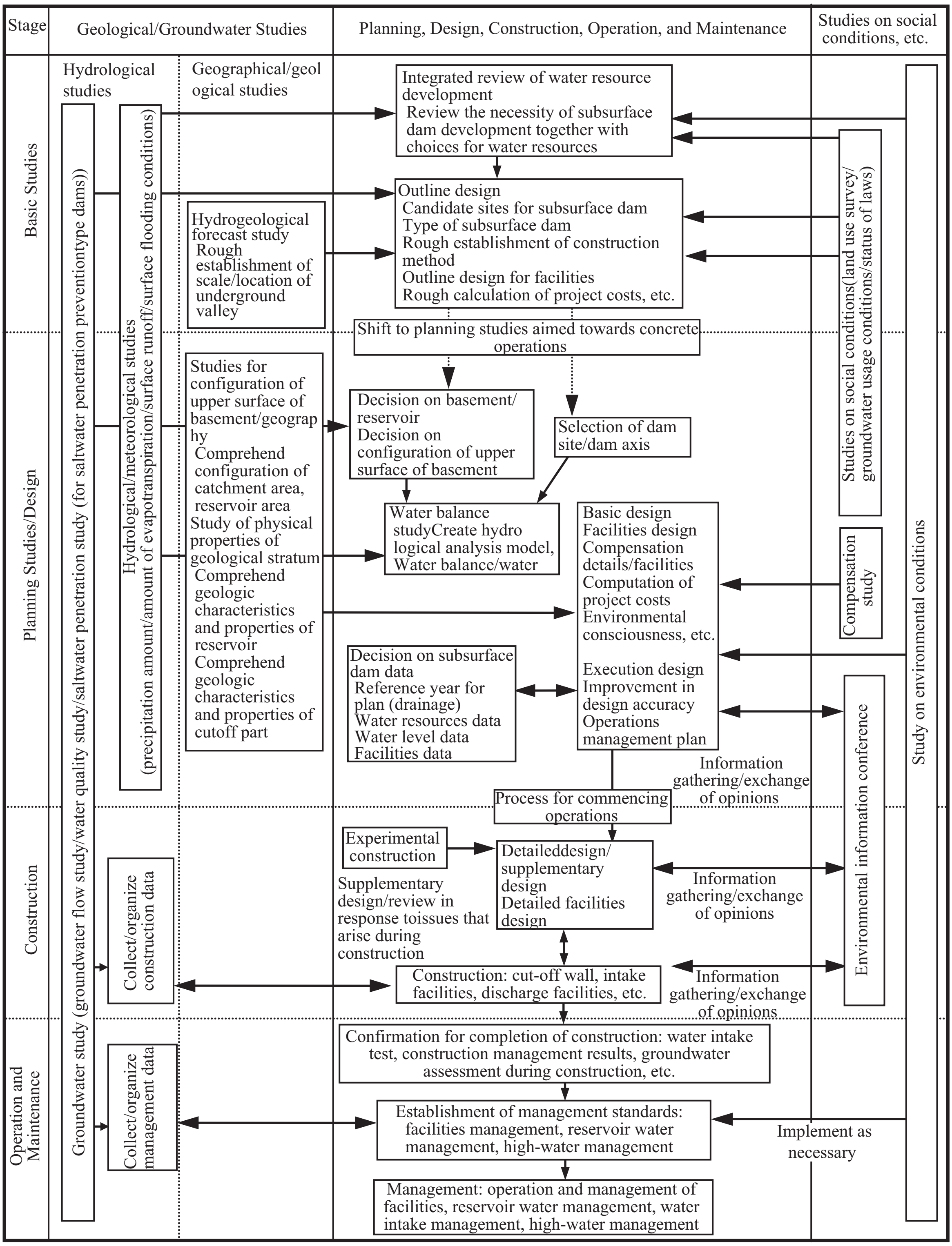
For basic studies, an integrated review related to water resource development using underground dams is conducted in accordance with the results of hydrologic studies (groundwater studies, and hydrological/meteorological studies) and hydrogeological forecast studies. During this stage, the candidate sites for the underground dam are selected and rough specifications for the underground dam are established together with the implementation of an outline design for the underground dam facility. Studies on social conditions, studies on the amount of water resources required, and environmental studies are also conducted in this basic studies stage.

During the planning studies/design, geological studies (studies on the geography/shape of the upper surface of the basement, and studies on the properties of geological layers) and hydrological studies (groundwater studies, and hydrological/meteorological studies) are conducted. The results of these studies are used to conduct a hydrological analysis (creation of a current hydrological model, water balance analysis, etc.) and to obtain data about the underground dam. In addition, the basic design (facilities design, compensation details/facilities, computation of project costs, environmental consciousness, etc.) and the execution design (improvement in design accuracy, and operations management plan) for the underground dams are implemented during this stage. Studies on social conditions, studies on the amount of water resources demanded, and environmental studies relating to restrictions on groundwater started in the basic studies stage are continued during this planning studies/design stage. In addition, compensation studies (water supplies to the downstream residents, etc.) are also implemented during the planning studies/design stage.

During the construction stage, experimental construction is conducted first to confirm the adequacy of the construction method. Actual construction begins based on the results of this experimental construction. In addition to implementing a detailed engineering plan based on the construction plan, supplementary design is carried out if new issues arise during construction.

Operation and maintenance (operation and management of facilities, management of reservoir water, management of water intake, management of high water, etc.) is carried out by the main management body. In addition, data obtained during the operation and maintenance stage can be used to confirm the accuracy of the hydrological analysis model as well as for the rationalization and streamlining of

Table 1. Flow of Water Resource Development Using Subsurface Dams[10]



operation and maintenance.

Construction of underground dams

1. Underground dams until 1990

Sand storage dams have been constructed in northwestern Africa (e.g., Libya), Namibia, Kenya, Sardinia, Austria, southwestern United States, and northern Mexico[1,8]. In Kenya, sand storage dams and subsurface dams are common in semi-arid regions with ephemeral sand rivers. They are used in combination with shallow wells located upstream of the dams. The wells are primarily used for domestic purposes, but in several cases also for small-scale irrigation[21]. In the United States, sand storage dams have been used as water sources for more than 100 years, e.g., a sand storage dam was built on bedrock to intercept the underflow of a stream and store water in the gravel bed above the dam about one mile west of Kingman, Arizona. Another sand storage dam was erected for impounding water in California, where numerous novel and experimental projects were carried out in 1890. The dam in California has a slender reservoir wall built across the Pacoima Creek in the San Fernando Valley to form an underground reservoir, whose storage capacity consists solely of the voids in the gravel bed filling the valley of the stream[22]. In 1960, a large sand storage dam (called a barrier dam) was constructed to control sediment from 80.5 km^2 of drainage area and to provide a stable base-level control, and the reservoir below the spillway elevation was nearly completely filled with sediment by 1961[7].

Subsurface dams have also been constructed in east Africa, Brazil, Afghanistan, India, and Japan. In Brazil, four subsurface dams were constructed in 1982 for the cropping of maize, cowpeas, and sorghum[2]. On the Yugoslav Adriatic Coast, some springs are protected by grout curtains against salination by the sea. In China, more than 20 underground reservoirs have been created with storage capacities between 1 x 10^5 and 1 x 10^7 m^3 in the karst regions for water supply, irrigation, industry, and power production[13]. In Japan, the first subsurface dam, called the Kabashima Subsurface Dam, with a storage capacity of approximately 20,000 m^3 and daily yield of 300 m^3, was constructed in 1973 as a water supply. Subsequently, the Minafuku experimental subsurface dam with a storage capacity of 700,000 m^3 was constructed by the Ministry of Agriculture, Forestry, and Fisheries (MAFF) and the Okinawa General Bureau in 1979 to clarify whether a larger subsurface dam could be constructed on Miyakojima Island. Five subsurface dams including the above-mentioned dams had been constructed by 1990[11]. In Korea, five subsurface dams with storage capacities of about 1-5 million m^3 had been constructed by grouting method for irrigation by 1990. In India, at least four subsurface dams had been constructed for irrigation with stone masonry, plastic bricks, and other materials by 1990[20,24].

The capacities of these underground dams are smaller than the underground dams constructed recently, and some dams have problems as described below.

2. Recent underground dams (after 1990)

After 1990, a new civil engineering technology called the mixed-in-place slurry-wall method made it possible to construct subsurface dams that store 1 million m^3 or more of groundwater (mega-subsurface dams)[14].

In southwestern Japan, MAFF constructed the first mega-subsurface dams, the Sunagawa subsurface dam and Fukuzato subsurface dam, on Miyako Island in 1988. Construction was completed in 1993, and the groundwater reservoir became fully recharged in 1995. After that, five subsurface dams were completed and six subsurface dams are still under construction by MAFF for irrigation using the mixed-in-place slurry-wall method.

In northern Burkina Faso, a subsurface dam was constructed by the Japanese Ministry of the Environment in 1998 in a fossil valley by excavating the aquifer layer up to the basement rock and building a dam body[6].

In five southern provinces of China, 52 underground dams had been constructed in the karst region by 1995. The total storage capacity of these dams reached 40 million m^3, which was enough to irrigate 8,900 km^2 of fields. After that, at least five subsurface dams were constructed in the river basin by grouting and by the clay-wall method, in which the cut-off wall is constructed using clay.

In the Agreste and Sertao areas of the interior of Pernambuco State in northeastern Brazil, about 500 small subsurface dams were constructed during the 1990s. Some were small structures up to 3 m deep, constructed under “government drought emergency job-generating programs” at sites selected by municipal committees without technical advice and follow-up. They were manually excavated, and plastic membranes and a large-diameter concrete-ring water-well was incorporated. Others were constructed under local initiatives by NGOs with specialist advice. These dams had similar-sized structures, were filled with only recompacted clay, and they did not have a well for water abstraction. The others were much larger structures up to 10 m deep (in areas of thicker alluvial cover) located according to technical criteria and constructed to support small-scale irrigated agriculture in areas with existing irrigated cultivation. They benefited from the use of mechanical excavators and incorporated impermeable plastic membranes, large-diameter water wells, and some technical monitoring[5].

In the Kitui District of Kenya, the SASOL Foundation began constructing underground dams in 1995, and around 500 underground dams now store water for livestock, minor irrigation, and domestic use. The typical heights of these dams ranged from 1 to 4 meters above the surface[3,19]. There were two types of construction: one using a wall facing filled with bricks or stones, and the other a timber framework filled with stones and mortar, but when stones were not available, other materials (e.g., plastic foil, galvanized iron, or clay lugs) were used. In some areas, wells were constructed close to the upstream side of the subsurface dams (at 200 m maximum distance from the riverbed) for daily water collection and small-scale irrigation[5].

In Ombla Spring, Croatia, many investigations and plans have been carried out since the 1980s for the construction of power plants. Underground dam construction projects may begin in the near future[26].

Table 2 shows recent (after 1970) underground dams reported in the reference articles listed at the end of this paper.

Table 2. List of recent underground dams

Country	Dam name	Dam type	Construction period	Dam height(m)	Dam length(m)	Total reservoir (1,000 m^3)	Construction method for cut-off wall
Japan	Kabashima	subsurface	1973,1979-80	24.8	58.5	20	Grouting
	Minafuku	subsurface	1977-1979	16.5	500	700	Grouting
	Tsunekami	subsurface	1982-1984	21.5	202	73	Slurry wall
	Tengakuma	subsurface	1987-1988	12.5	129	17	Grouting
	Ryorigawa	subsurface	1991	4.2	151.6	42	Thin steel sheet
	Nakajima	subsurface	1991-1992	24.8	88	27	Mix-in-place
	Waita	subsurface	1991-1992	7.5	105.3	12	Slurry wall
	Sunagawa	subsurface	1988- 1993	49	1677	9,500	Mix-in-place
	Miko	subsurface	1995	39.3	192	23	Mix-in-place
	Shitoro	subsurface	1997	8.5	44.1	18	N.A.
	Fukusato	subsurface	1994-1998	27	1790	10,500	Mix-in-place
	Kikai	subsurface	1993-1999	35	2281	1,800	Mix-in-place
	Giiza	subsurface	1999-2001	53	969	390	Mix-in-place
	Komesu	subsurface	1993-2003	69.4	2,320	3,460	Mix-in-place
	Kaniin	combined[*1]	1995-2005	52.1	1,088	1,580	Mix-in-place
	Yokatsu	subsurface	1999-2008	67.6	705	3,963	Mix-in-place
	Ie	subsurface	2004-	55.9	2612	1,408	Mix-in-place
	Izena	subsurface	2005-2008	14	488.4	238	Steel sheet pile
	Okinoerabu	subsurface	2007-	48.2	2414	1,085	Mix-in-place
	Nakahara	subsurface	2009-	55	2350	10,500	Mix-in-place
	Bora	subsurface	2009-	26	2600	2,200	Mix-in-place
Korea	Eean	subsurface	1983	5-7	230	4,143	Grouting, concrete wall
	Namsong	subsurface	1986	10-20	89	4,017	Grouting
	Okseong	subsurface	1986	10	482	2,850	Grouting
	Gocheon	subsurface	1986	7.5	192	1,543	Ferroconcrete wall
	Wooeel	subsurface	1986	6-7	778	2,457	Clay wall
	Ssangcheon	subsurface	1995-1998, 2000	4-27	840	N.A.	Slurry wall, concrete wall
China	Balisha River	subsurface	-1987	N.A.	756	N.A.	Grouting
	Huangshui River	subsurface	-1995	40.1	5,996	N.A.	Grouting
	Dragon River	subsurface	-2000	N.A.	N.A.	N.A.	Directional jet grouting
	Jia River	subsurface	-2001	31	3,890	N.A.	Grouting
	Wang River	subsurface	-2004	N.A.	13,500	N.A.	Grouting
	Dagu River	subsurface	-2004	N.A.	2,600	N.A.	Clay wall
India	Anangana	subsurface	1979	5	160	15	Plastered brick, tarred felt, plastic sheet
	Ottapaiam	subsurface	1962-1964	5-9	155	N.A.	Plastered brick
	Ootacamund	combined [*1]	1981	3.5	N.A.	N.A.	Plastic sheet
	Shenbagathope	subsurface/ sand storage	1987	3.5	15	N.A.	Stone masonry
Ethiopia	Bombas	sand storage	1981	3.8	N.A.	N.A.	Concrete block
	Gursum	subsurface	1981			N.A.	Stone masonry
Burikna-Faso	Nare	subsurface	1997-1998	3-11	210	1,800	Buried earth dam
Brazil	about 500 dams	subsurface	1990s	3-110	N.A	N.A	N.A.
Kenya	about 500 dams	subsurface/ sand storage	1990s	N.A	N.A	N.A	Filled with bricks, stones, mortar
U.S.A	Pacoima Notch	subsurface (submerged)	1988	15.6	165	N.A	Rubble masonry

[*1] surface/subsurface

Problems with underground dams and future research topics

1. Sedimentation

Falkenmark et al.(2001) reported that some 80% of the dams did not store enough groundwater because they were designed without specialists[4]. Nilsson (1988) suggests it takes three or more years to build a fully effective sand-storage dam because it is necessary to fill sand-storage dams with coarse sediment[16]. This allows the reservoir to gradually fill up with coarse sediment as higher flow velocities flush fine particles across the dam. The coarse sediments increase the potential storage of the dam because they have higher porosity. Furthermore, abstracting water from the reservoir is easier with coarse sediments. Nevertheless, some Kitui dams were built in half a year[3]. The setting and design of underground dam structures necessitate technical expertise, especially to avoid siltation and leakage.

2. Problems in the karst regions (flooding, collapse, salination)

Milanovic (2004) reported the unfavorable consequences of underground storage in the karst regions[13]. In China, plugging underground flow to store water for irrigation in a cave system caused a flood in a depression of arable land 2 km upstream, and 240 persons had to be evacuated. In Herzegovina, inadequate manipulation to plug a karst channel caused an abrupt increase in water pressure in the cave system, and the surface above the underground reservoir collapsed. In another case, the experimental plugging of a karst channel caused numerous new springs to appear on the hill slopes. Because of the explosion of air in the ground, a road on the hillside above the plugged estavelle began to slide, and many houses were damaged at a distance of 250 to 300 m above the plug. (*Estavelle is a ground orifice, which, depending on weather conditions and the season, can serve either as a sink or as a source of fresh water.)

Along the Yugoslav Adriatic coast (now Montenegro), grout curtains to cut groundwater flow caves caused an increase in spring water pressure, accompanied by a great increase in discharge.

In Japan, groundwater sprang up through a cave during heavy rain after the completion of an underground dam, and fields became soaked with water. Drainage facilities were later constructed[17].

These results show the complexity of the underground routes of natural cave streams and the impact of retention capacity of underground karst-influential areas.

3. Water quality

An underground dam drastically changes the groundwater level and groundwater flow from natural conditions, and this change influences the quality of the groundwater. It is important to estimate the impact of underground dam construction on groundwater quality.

(1) Salination

Soil salination is a serious problem in arid and semi-arid areas. The presence of saline soils can lead to significant levels of groundwater salination, which can be further aggravated by direct evaporation when impoundment results in a shallow water table. Sites with saline soils should be avoided for dam construction[5]. As mentioned above, salt extracting plants can help combat this problem if they are harvested and removed from the site. However, the balance between the amount of salt that the plants extract and the amount of salt that they introduce by increasing transpiration is unknown. The effective control of salination requires a deeper understanding of its formation[25].

(2) Nitrate Contamination (case study of Miyakojima Island, Japan)

The Japanese government started constructing the first mega-underground dam, the Sunagawa subsurface dam, for irrigation 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_3-N in the groundwater on the island was about 5 mg/l in 1975, but has subsequently increased because of the application of fertilizers to sugarcane fields[12]. Before the construction of the underground dam began in 1988, the concentration of NO_3-N in the groundwater reached about 10 mg/l, which is the upper limit for drinking water in Japan. In 1991, two years before the completion of the Sunagawa subsurface dam, NO_3-N concentration ranged from 7.0 to 11.9 mg/l (Fig. 5). NO_3-N concentration started to increase from upstream to downstream areas. Although the data is limited, NO_3-N concentration was highest around the dam.

In 2000, seven years after the completion of the Sunagawa subsurface dam, NO_3-N concentration ranged from 2.69 to 9.75 mg/l with a mean value of 6.38 mg/l (Fig. 6). The highest concentration was at downstream of the catchment before completion of the underground dam, and the high concentration zone remained near the cut-off wall after its completion.

In 2003, two years after the groundwater began to be used for irrigation, NO_3-N concentration ranged from 2.14 to 8.34 mg/l with a mean of 5.77 mg/l (Fig. 7). The high concentration zone near the cut-off wall observed in 2000 disappeared by 2003.

Figure 8 shows fluctuations in NO_3-N concentration in the groundwater sampled near the cut-off wall from 1988 to 2001 (bold line).

The monitoring period was divided into three stages to examine the impact of the underground dam on the groundwater environment: before completion of the underground dam (1988–November 1993), after completion but before the reservoir was fully recharged (December 1993–September 1995), and after the reservoir was fully recharged

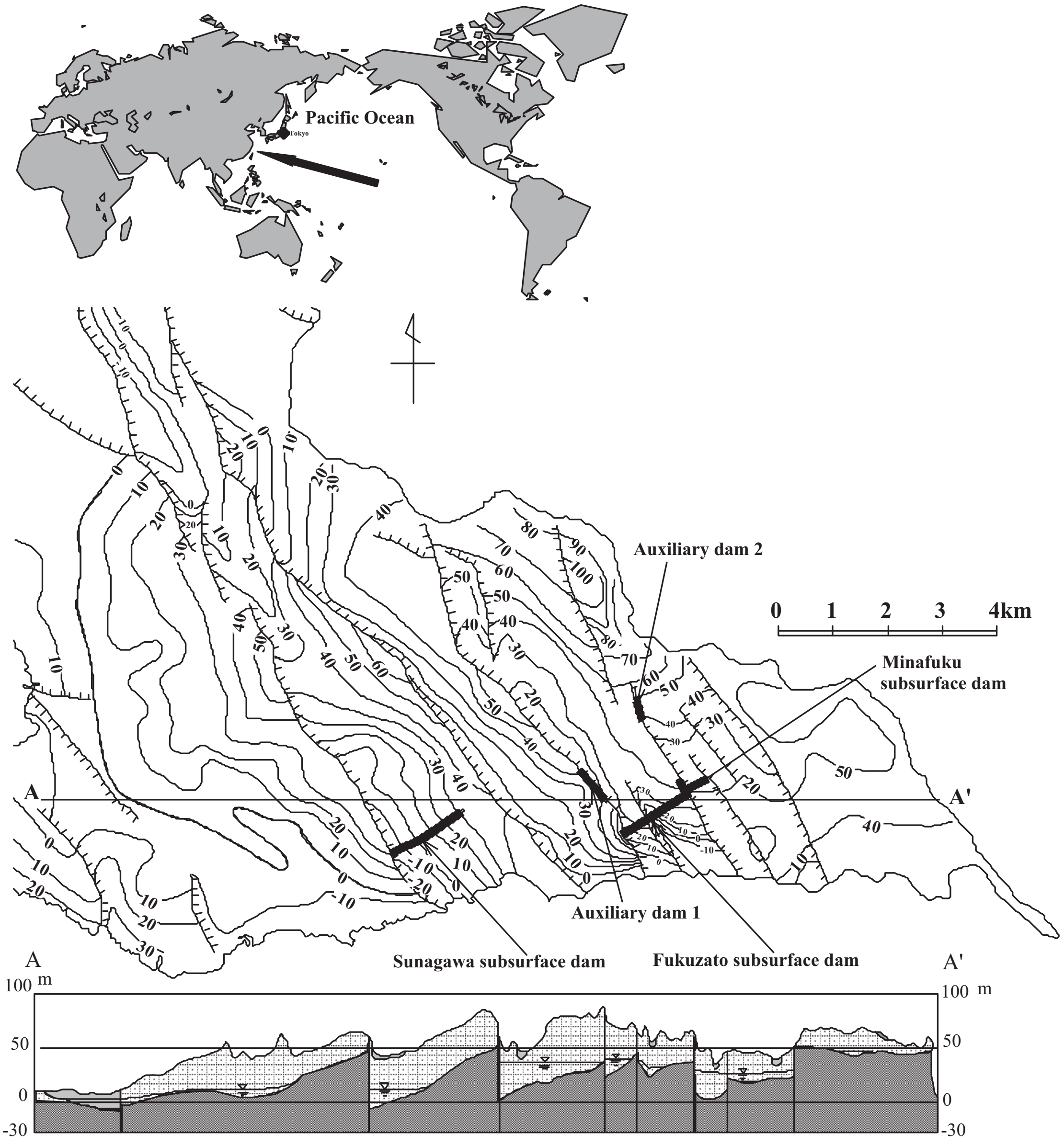


Fig. 4. Geological cross-section and basement contour map of the study area

▬:Subsurface dam axis, ▭:Surface soil (clay), ⟍:Fault, ▨:Aquifer (limestone), ∽:Basement contour, ▩:Basement (mudstone)

and the water began to overflow (October 1995~February 2001). The fluctuations in NO_3-N concentration could be characterized by main component (annual average: dotted line) and accessory component (maximum and minimum range: thin lines). The main component described the overall trend of NO_3-N concentration, which decreased from 12.0 mg/l in 1988 to 8.2 mg/l in 2001. This decrease in NO_3-N has also been reported in the groundwater of catchments without underground dams[23]. Therefore, this may be the general trend on Miyako Island. This trend was notably unaffected by the construction of the Sunagawa subsurface dam. These results show that construction of an underground dam and pumping stored groundwater for irrigation strongly affects groundwater quality.

4. Future research topics

The problems with underground dams listed here may be very few compared to the problems actually occurring. However, the causes are divided into two types:

One cause originates from human activities. Ertsen et al. (2009) pointed out that problems often arise because the planning and construction are not carried out by a specialist[3]. Moreover, when the operation of the facilities is not carried out properly after completion of the underground dam, flooding or water shortages occur. If a specialist is not available, a comprehensible manual is necessary. Water

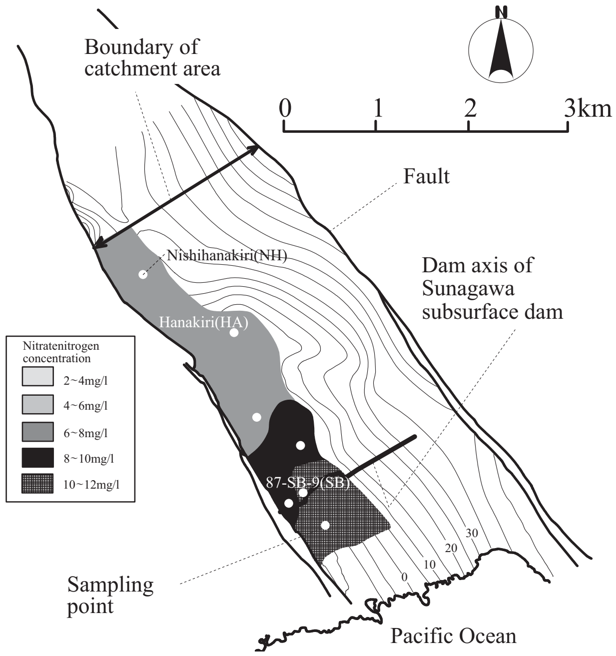


Fig. 5. Distribution map of NO_3-N at 5 m below the groundwater table in 1991

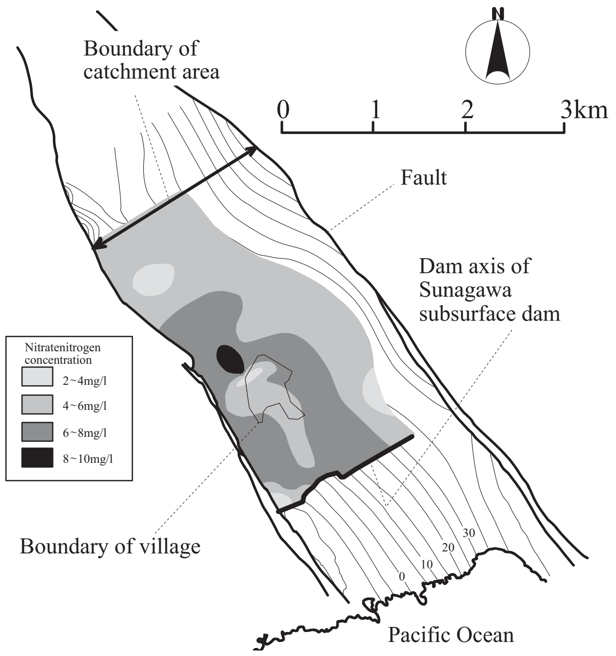


Fig. 7. Distribution map of NO_3-N at 5 m below the groundwater table in 2003

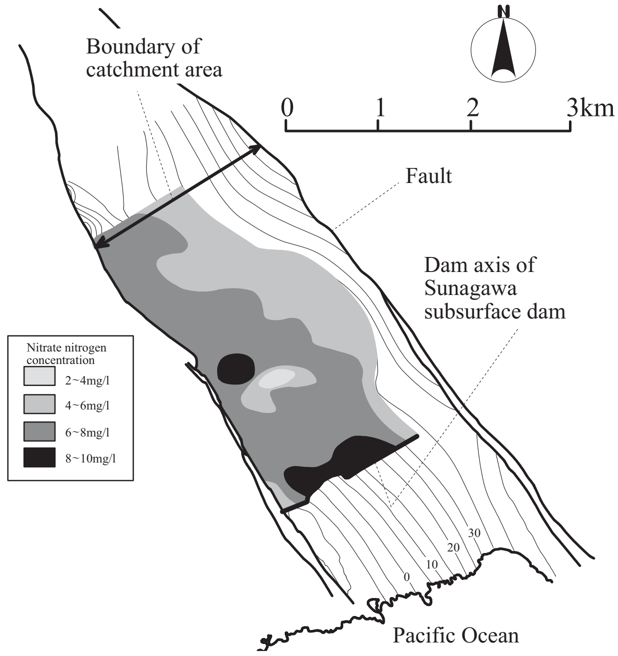


Fig. 6. Distribution map of NO_3-N at 5 m below the groundwater table in 2000

quality management in the underground dams is also an important subject for the future because there are very few studies on water quality after the construction of an underground dam. For this purpose, long-term monitoring should be carried out after construction of underground dams.

The other cause is complexity of geological features. Accurate forecasts are especially difficult because the aquifer and basement in karst regions are not noticeably homogeneous. For example, the infiltration of salt water from the base occurs to some degree, and salt water removal wells have been set up in one underground dam basin in Japan[15]. Researchers and specialists should share information about survey techniques for the planning and construction of underground dams.

Guidelines such as JGRC (2006) should exist in many countries where underground dams are built[10]. To manage problems, it is important that countries exchange information on these skills guidelines in the future. The Technical Committee on Groundwater Dams in the International Commission on Large Dams (ICOLD) is preparing a technical bulletin named “Guidelines for the Development and Usage of Groundwater Dams”. Member countries include Brazil, Burkina Faso, China, Macedonia, India, Iran, Japan, Korea, Morocco, Nigeria, Slovakia, Thailand, and the United States. There are many underground dams in the world now, and there is much information to be shared.

Conclusion

Computers have improved rapidly since the 1990s and made complex simulations possible. Research and construction technology have also improved. As a result, plans for underground dams have become more accurate, and larger projects that meet the above-mentioned requirements are now possible. However, we still encounter "unexpected" phenomena, so these problems should be carefully analyzed and information on these problems should be shared.

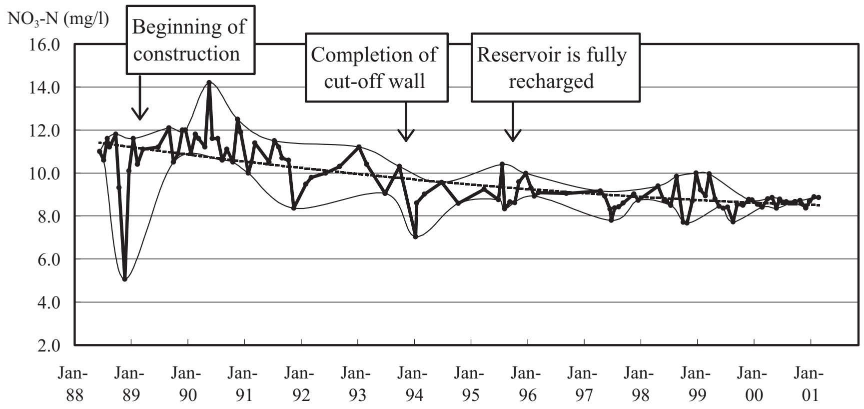


Fig. 8. Fluctuations of NO_3-N in groundwater of the catchment of the Sunagawa subsurface dam
—•— : SB (50 m upstream form dam axis).

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