Technical Reference for Effective Groundwater Development

March 2004

Japan Green Resources Agency

J-Green

Japan Green Resources Agency (J-Green) was incorporated in 2003 based on the Japan Green Resources Agency Act.

In Japan, J-Green is carrying out comprehensive development projects to promote agriculture and forestry based on the master plan prepared by the Ministry of Agriculture, Forestry and Fisheries, for revitalizing communities in agricultural and mountainous areas and protecting national resources.

J-Green has been engaged in agriculture and community development assistance projects overseas. To deal with global environmental issues that have attracted growing attention in recent years in particular, J-Green is actively conducting investigations into desertification and soil erosion prevention measures.

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Preface

Japan Green Resources Agency (J-Green) (established following the dissolution of its former body, Japan Green Resources Corporation, in October 2003) has the experience of having constructed subsurface dams on Japan's Miyakojima Island located in the subtropical climate zone, during the 1990s. This small island with an area of less than 200 km^2 is now complete with two large-scale subsurface dams with a gross reservoir capacity of approximately 10 million m^3. With these subsurface dams, Miyakojima Island is now able to promote high-yield, stable agricultural production.

Thanks to the success of the project, the subsurface dam has attracted growing attention as one of the many options for water resource development methods. The subsurface dam has a number of advantages: the absence of surface flooding assures almost complete absence of effects on land use and the ecosystem, and the absence of sedimentation enables it to function almost permanently. The loss of reservoir water from evaporation is also reduced. This last characteristic makes the subsurface dam superior over other water resource development methods in dry and semi-arid regions.

As part of an international cooperation project for agricultural and rural community development, J-Green has been conducting surveys since 1998 to examine the possibilities of promoting agriculture based on the construction of subsurface dam, with subsidies from the Ministry of Agriculture, Forestry and Fisheries of Japan. The objectives of the surveys are to apply the results from subsurface dam projects in Japan to dry and semi-arid regions and develop wide-area, stable agriculture and other production activities.

In addition to the considerable technical information obtained and lessons learned from subsurface dam projects in Japan, valuable expertise was gained during the basic study. This "Technical Reference for Effective Groundwater Development (Technical Reference)" summarizes the information and knowledge learned from the study. This technical reference comprises seven chapters as shown below.

- Chapter 1: Processes leading to the production of this Technical Reference
- Chapter 2: Objectives of water resource development and functions fulfilled by each hydraulic structure
- Chapter 3: Assessment of the propriety of various groundwater development and conservation measures and the selection methods for subsurface dam development sites under the preliminary survey
- Chapter 4: Examination of survey methods targeting subsurface dam development sites and subsurface dam operation plans under the site survey
- Chapter 5: Precautions when designing subsurface dam related facilities
- Chapter 6: Construction plans and examples of subsurface dam related facilities
- Chapter 7: Management of subsurface dam reservoir water, and maintenance and management of subsurface dam related facilities

This technical reference defines the survey, planning and design processes for subsurface dam development. However, in order to increase the effectiveness of discussions, many pages are devoted to the results of site investigations conducted in Indonesia and Mexico.

Subsurface dam development is accompanied by technical risks because of the lack of accurate information available prior to the start of construction. It is also accompanied by considerable financial burdens due to generally high construction cost. The participation of concerned individuals spread over wide areas is therefore essential for the success of subsurface dam development. The decision of whether or not to go ahead with subsurface dam development should be discussed from many angles based on accurate survey results.

This “Technical Reference” shows one possible model of development proposed by J-Green, and should be improved depending on future site conditions and through repeated courses of surveys and projects. We hope that this Technical Reference will help raise the interest of local residents, local governments and many other concerned individuals in need of new water resource development on the mechanism and necessity of subsurface dam. Moreover, we would be delighted if the interest leads to discussions by local residents, administrative agencies and specialists and finally develops into project planning and implementation. We sincerely hope that this Technical Reference will be of some help in the development of agriculture-oriented districts in desperate need of water resources.

We would like to express our gratitude for the guidance and cooperation received from many individuals both at home and abroad during the production of this Technical Reference. We would like to particularly thank the government officials of Indonesia, Mexico and China, who provided considerable assistance and cooperation during the basic study, the Ministry of Agriculture, Forestry and Fisheries of Japan, Japanese embassies in Indonesia, Mexico and China, overseas offices of Japan International Cooperation Agency (JICA), and engineers and all the other concerned parties who participated in the survey.

March 2004

Japan Green Resources Agency
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Technical Reference for Effective Groundwater Development

Chapter 1 Introduction

1.1 Background

1.1.1 Subsurface dam Projects Undertaken in the Past

During the 1990s, the Japan Green Resources Agency (J-Green) constructed subsurface dams on Miyakojima Island located in Japan's subtropical climate zone. Miyakojima, a small island with an area of less than 200 km^2, is now complete with two large-scale subsurface dams with a gross reservoir capacity of approximately 10 million m^3. These subsurface dams, constructed on an unprecedented scale, provide a base for agricultural promotion. They are the first example of widely increasing the recognition of the subsurface dam as an optional method for developing water resources.

There is a short history and only a few examples of subsurface dam projects in Japan. A clear trend is also observed in regional distribution: for example, large-scale subsurface dam with a gross capacity exceeding 1 million m^3 are concentrated in subtropical regions and small-scale subsurface dam are found only in remote islands and narrow peninsulas. Despite an increase in the number of options for water source development, subsurface dam construction is still generally regarded as an extraordinary method.

From a global point of view, the technology employed to intercept groundwater has a long history, reportedly dating back to ancient civilization. Half the number of subsurface dam now known to be present in the world are located on the African continent, and a large portion of these dams are located in semi-arid regions in which there is a clear division between dry and rainy periods and are used for small-scale community service water. Some of these dams have a sediment control dam constructed to prevent evaporation and there are many examples of keeping water in the sediment intentionally accumulated in the dam.

1.1.2 Implementation of the Basic Study

Areas such as dry regions with disadvantageous conditions for surface dams due to large water loss from evaporation are considered to have more of an incentive to develop subsurface dams and to find more applications for these dams. It is important to preserve precious water resources as long as possible, while minimizing its loss. Particularly in semi-arid regions (with clear division between dry and rainy periods) where a rainy period is followed by a long dry period, it is also essential to store water during the rainy period and promote economical use of the water during the dry period.

Under these conditions, groundwater development is effective. To ensure optimum stability in the use of groundwater, it is important to undertake measures to increase groundwater recharge or protect groundwater. Subsurface dam development provides a potentially effective means for implementing such measures.

The Japan Green Resources Agency initiated a basic study in 1998 on subsurface dam projects undertaken in Japan, the results of which would be effectively applied to measures for increasing groundwater recharge and protecting groundwater in dry and semi-arid regions. With the prospect that the study would lead to the overseas cooperation project for agricultural and rural community development, the Japanese Ministry of Agriculture, Forestry and Fisheries provided subsidization. The study for overseas agricultural development was implemented under the name “Basic Study for Environmentally Protective Water Resource Development.”

1.2 Items for Examination

The purposes and details of the Basic Study for Environmentally Protective Water Resource Development are briefly explained below. The study commenced in 1998.

1.2.1 Purposes of the Study

Due to their climatic conditions, dry and semi-arid regions are highly dependent on groundwater as a water source. If irregular rainfalls are the cause of fluctuations in the groundwater reserve, it is important to take measures to increase groundwater recharge and to protect groundwater at the same time.

Stable intake and use of groundwater for irrigation would allow systematic and stable agricultural production. This has proven to be a major factor in improved income and living standards in many countries where agriculture is the foundation of the economy.

Since subsurface dam development requires no filling of surface reservoirs, current land use and ecosystems are maintained and this means that subsurface dam development is environmentally protective. It is, therefore, worth promoting subsurface dam development as a measure to increase groundwater recharge.

In view of the points mentioned above, the basic study examined the two points below.

(1) Preliminary Survey

The preliminary survey is designed to identify factors detrimental to groundwater development and measures to solve such factors, examine comprehensive measures to develop and protect groundwater, and at the same time, identify the relationship of subsurface dam development with such comprehensive measures.

(2) Site Survey

The site survey is designed to briefly examine the survey, planning and design processes regarding subsurface dam development, one of the measures to increase groundwater recharge, and to develop the proposal for a plan to operate subsurface dams that can contribute to sustainable agricultural and rural community development.

1.2.2 Target Areas for the Study

Before starting the study, the target areas were narrowed down to only a few, for the purpose of carrying out intensive, more on-the-spot examination to obtain effective results.

At the beginning of the study, the characteristics of the regions considered particularly in need of subsurface dam development and where such development would prove effective were defined as follows:

(1) Islands with a small catchment area that makes stable water use difficult

(2) Coastal regions where excessive groundwater pumping has caused severe saltwater infiltration to groundwater

Two target areas, the eastern part of Indonesia and the northwestern part of Mexico, were selected based on the following criteria: representative regions that fall, respectively, under Categories (1) and (2) above in countries with an economy of a certain size specifically interested in subsurface dam development. Subsurface dams are classified into two types applicable for different purposes: the dam type and the saltwater infiltration prevention type. Categories (1) and (2) cover regions that are highly likely to adopt the dam type and the saltwater infiltration prevention type, respectively. In consideration of this, the study areas were selected as follows:

(a) Eastern part of Indonesia: To examine the possibility of constructing mainly the afflux dam

(b) Northwestern part of Mexico: To examine the possibility of constructing mainly the saltwater infiltration prevention dam

Additionally, a subsurface dam project, aimed at combined use of the afflux dams and saltwater infiltration prevention dams, is planned in China. The examination processes for the project were also reviewed.

1.2.3 Matters for Study

The following study was specifically conducted:

(1) Preliminary Survey

- Selection of appropriate sites for subsurface dam development

  Collection and analysis of available existing data (including data on topography, geology, meteorology, hydrology, land use and water use) and site reconnaissance
- Identification of the present state of groundwater problems and collection of examples of measures undertaken

  Data collection and on-site confirmation

(2) Site Survey

From the appropriate sites for subsurface dam development in Indonesia and Mexico selected through the preliminary survey, one district each was selected as a model district for detailed examination of the possibility of developing the afflux dam and the saltwater infiltration prevention dam. The following surveys were conducted in these model districts:

- Survey on natural conditions
  Topographic and geological survey (Ground surface survey, topographic survey, geophysical survey and boring survey)
  Meteorological and hydrological observation (Including precipitation, river discharge and groundwater level)
- Survey on social conditions
  Current state of land and water use
  Agricultural development potential
- Examination of the cut-off wall construction method for the subsurface dam
- Hydraulic analysis
  Numerical simulation analysis (Including water balance and groundwater flow)
  Assessment of the effect of subsurface dam construction and determination of the water yield

1.2.4 Compilation of Survey Results

As a compilation of the results of the surveys above, the Technical Reference for Effective Groundwater Development was produced. This collection of study examples is used as reference when preparing an agricultural and rural community development plan with the focus on measures such as subsurface dam development to increase groundwater recharge and protect groundwater

1.3 Progress

1.3.1 Flow of the Study

The flow and schedule of the study are summarized in Figure 1.3.1.

The results of two surveys, the Preliminary Survey (1998 to 2001) and the Site Survey (1999 to 2003) that followed, were compiled to produce the Technical Reference for Effective Groundwater Development.

The years in which surveys were conducted in target countries are shown in Figure 1.3.2.

The two surveys (carried out during the 1998 to 2003 period) were conducted only in Indonesia and Mexico. The surveys in China, on the other hand, started in 1998 and ended with a technical exchange seminar in 1999.

Figure 1.3.1 Flow of the Study

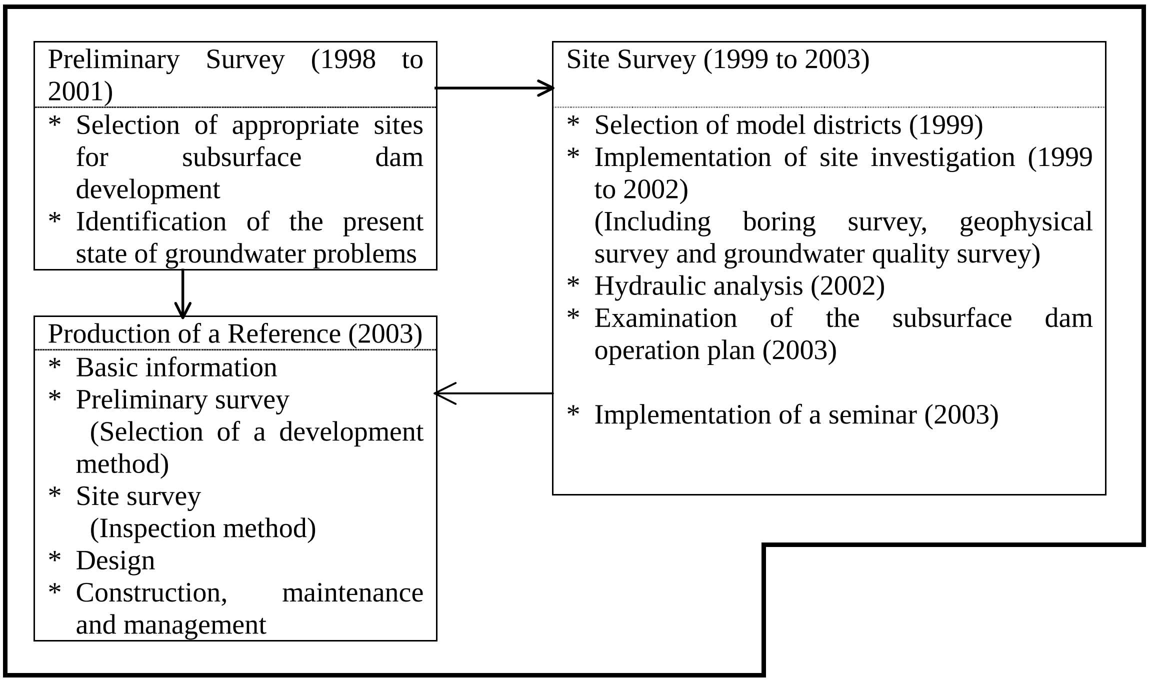


Figure 1.3.2 Survey Years

Year	1998	1999	2000	2001	2002	2003
Preliminary survey	Indonesia Mexico China	→ →	→ →	→ →		
Site survey		Indonesia Mexico China (*)	→ →	→ →	→ →	→ →
<Main activities> Collection of available existing data Site investigation Hydraulic analysis Implementation of a seminar Production of a technical reference						

* A technical exchange seminar was held concerning planning and design.

1.3.2 Survey Results

The survey results are summarized in Table 1.3.1, Table 1.3.2 and Table 1.3.3.

The site survey was conducted in the two model districts selected: Ketes district, Bali Province in Indonesia and La Mission district, Baja California State in Mexico.

Table 1.3.1 Survey Results (Preliminary Survey)

Year	Principal Items for Examination	Survey and Examination Details	
		Indonesia	Mexico
1998	* Identification of the present state of groundwater development needs	Obtained information from the Indonesian Government about the regions that had expressed the need for groundwater development. Selected 84 districts from Bali Province and East and West Nusa Tenggara Provinces.	Collected survey data produced by the Mexican Government on the present state of the water balance in each catchment area. Found that regions with a tendency for excessive water use are concentrated in the California Peninsula.
1999	* Examination of the candidate site selection method for subsurface dam development	Selected six districts ideal for groundwater development from among 84 districts that had expressed the need for development based on hydrological and geological conditions (of which one district was selected as the model district for the site survey).	Selected three districts ideal for groundwater development from among nine districts with a tendency for excessive groundwater pumping based on hydrological and geological conditions (of which one district was selected as the model district for the site survey).
2000		Obtained general information on the subsurface geologic structures of the districts ideal for development as mentioned above (five districts excluding the model district) for assessment.	
	* Identification of the present state of groundwater problems and collection of examples of measures undertaken		Identified the present state of salt damage (soil salt buildup and saltwater infiltration to groundwater).
2001		Identified the present state of conflict between water supply for irrigation and that for tourism and the measures to solve the problem.	Identified water-saving irrigation plans.
	* Comprehensive examination of groundwater development and protection plans	Comprehensively examined the ideal groundwater development and protection in consideration of the circumstances described above and determined the importance of the subsurface dam -> Systematically sorted out data in the technical reference produced.	Comprehensively examined the ideal groundwater development and protection in consideration of the circumstances described above and determined the importance of the subsurface dam -> Systematically sorted out data in the technical reference produced.

Table 1.3.2 Survey Results (China)

Year	Principal Items for Examination	Survey and Examination Details
1998	**Preliminary survey** * Identification of the present state of groundwater development needs	Identified the factors necessitating the examination of the subsurface dam construction plan for Dalian in Liaoning Province and identified the current state of poorly satisfied water demand.
1999	**Site survey** * Collection of construction technology data	Collected general information regarding test construction of a subsurface dam by the Geological Research Institute, Hydro-geology Agency of Liaoning Province conducted for the purpose of constructing a subsurface dam that serves in the dual role of afflux dam and saltwater infiltration prevention dam, and regarding the design and construction plans produced following the test construction. High-pressure cement grouting method.
Summary of results		Identified the natural and social conditions in the site ideal for subsurface dam development based on the information above, collected construction technology information that can serve as reference for subsurface dam development and at the same time held a technical exchange seminar.

Table 1.3.3 Survey Results (Site Survey)

Year	Principal Items for Examination	Survey and Examination Details	
		Afflux dam (Indonesia)	Saltwater infiltration prevention dam (Mexico)
1999	* Selection of candidate model districts * Identification of the present state of agriculture and living conditions * Examination of the construction method	Selected Ketes district in Bali Province from among six districts ideal for development. The district, although having low income standards, has diverse forms of agriculture. Excavation and replacement methods.	Selected La Mission district in Baja California State from among three districts ideal for development The district grows vegetables on irrigated farmland and grows wheat and animal feed on rain-fed farmland. Ditching and solidifying agent replacement methods.
2000 – 2001	* Collection of meteorological, hydrological and topographical data * Conceptual design of a subsurface dam in consideration of the construction method and meteorological conditions * Detailed site investigation (including geological investigation) necessary for design	Collected data on nearby rainfall of the past 10 years, produced a topographic map and measured river discharges. Created a design that uses a cut-off wall installed less than 30 m down into the hydraulic basement to store surplus water during the rainy period and allows stable use of the stored water during the dry period. * Obtained general information on the hydraulic basement shape -> seven traverse courses of electric prospecting (2000) * Boring survey (2000 to 2001) (1) 3 locations for identification of basement rock (2) 2 locations for identification of aquifer prosperity	Collected hydrological and meteorological data of the past 30 years, analyzed aerial photographs, and observed groundwater levels, river discharges and water quality. Created a design that uses a cut-off wall installed in the narrow pass of the hydraulic basement and allows long-term water balancing and water quality management with a probability of flooding occurring once in 10 years. * Obtained general information on the hydraulic basement shape -> nine traverse courses of electric prospecting (2000) * Boring survey (2000 to 2001) (1) 5 locations for identification of basement rock (2) 3 locations for identification of aquifer prosperity
2002 – 2003	* Hydraulic analysis (1) Assessment of the effect of subsurface dam construction (2) Examination of the subsurface dam operation plan	Created a model to reproduce the current state of the water balance and groundwater flow based on the collected data mentioned above. Forecast the water balance using the model. Examined the intake and drainage of the water resource to be newly developed.	Created a model to reproduce the current state of the water balance, groundwater flow and saltwater infiltration based on the collected data mentioned above. Forecast changes in the water balance and salinity using the model. Examined the intake and drainage of the water resource to be newly developed.

Summary of results		Estimated the cut-off wall specifications: 30 m in depth, 300 m in length and 100,000 tons in storage. Determined the sustainable water yield (1,000 m^3/day).	Estimated the cut-off wall specifications: 60 m in depth and 500 m in length and reduced salinization in the reservoir area. Flexibly adjusted the groundwater level in the reservoir area in anticipation of flooding.
2003	* Drafting of the technical reference * Production of the technical reference that reflects opinions of concerned parties expressed during the seminar	Produced a reference for the examination processes described above.	Produced a reference for the examination processes described above.

1.3.3 Collaborative and Cooperative Relationship Formed during the Surveys

(1) Indonesia

Technical issues regarding the subsurface dam were examined through collaboration with the Directorate General of Water Resources, Ministry of Settlement and Regional Infrastructure and the Research Institute for Water Resources of the same ministry. Agriculture-related investigations were carried out in collaboration with the Directorate General of Agricultural Facility, Ministry of Agriculture.

(2) Mexico

Technical issues regarding the subsurface dam were examined during joint investigations with the International Cooperation Department of the National Water Commission (CNA). The CNA was also responsible for meteorological and hydrological observation. Agriculture-related investigations were carried out in collaboration with the International Department, Ministry of Agriculture, Livestock and Rurality Development.

(3) China

Technical issues regarding the subsurface dam were examined in collaboration with the Ministry of Land and Resources, Department of State.

1.4 Purposes of This Technical Reference

The Technical Reference for Effective Groundwater Development is a compilation of knowledge obtained from the Basic Study for Environmentally Protective Water Resource Development. The study, carried out as part of the overseas cooperation project for agricultural and rural community development and targeted at areas suffering from a shortage of water resources for agricultural purposes, examined the possibility of further agricultural development based on subsurface dam construction.

Subsurface dam development imposes considerable technical risks and financial burdens because of the lack of accurate prior information about underground conditions and the generally high construction cost. Since the decision of whether or not to go ahead with subsurface dam development should be discussed among many concerned individuals spread over a wide area, it is important to provide information from highly accurate surveys for decision-making purposes. The authority that provides such information, therefore, plays an important role. This technical reference, based on the premise that the subsurface dam is one of the options for water resource development, defines what kind of basic information must be available for decision-making purposes during the drafting of plans and generalizes the processes for preparing basic information, in order to improve efficiency during studies and projects.

To further increase its applicability, this technical reference examines the processes of an on-site case study and the results obtained.

Chapter 2 Basic Information

This chapter first summarizes the purposes of water resource development and functions fulfilled by each hydraulic structure, then, briefly reviews various water resource development methods for comparative examination to determine the characteristics of subsurface dam development. Also presented are matters for consideration in each stage leading to subsurface dam development.

2.1 Necessity of Water Resource Development

2.1.1 Distribution of Water Resources

Water present on the earth's surface is unevenly distributed spatially and temporarily. Lvovich (1973), who found no sense in regarding water resources on the earth's surface as a fixed amount of reserves, focused on water circulation and estimated the land water balance for each continent. According to his estimate, the average annual precipitation on the earth's entire surface is 834 mm, of which 540 mm is lost through evaporation. The remaining 294 mm, which moves on the ground surface or through the ground and finally flows into the seas, forms freshwater resources. These freshwater resources form the water cycle – rainfall, evaporation and gravitational flow.

Water use is influenced by limitations associated with the water cycle and at the same time may alter water circulation patterns. To determine the amount of valuable freshwater reserves, it is important to regard freshwater resources as being fluid. This means that the amount of freshwater reserves must be determined on a time basis, not at certain time points. From this perspective, the water yield can be defined as follows:

Water yield: Amount of water that runs through accessible areas (per unit time)

The above definition suggests two possible ways of increasing the potential water yield:

(1) To lead water into accessible areas or expand accessible areas

(2) To reduce the dead outflow, for example, by retarding the flow velocity to make it easier to capture water

2.1.2 Role of Water Resource Development

The necessity of water resource development arises when there is a gap between the water yield and water resource demand. Water resource development is aimed at increasing the water yield up to the level of demand.

Water resource development is significant not only in that it can respond to the water demand but also in that it can enrich the land-based water cycle and create new possibilities for diverse activities. The following section briefly summarizes the objectives of water resource development.

Water resource development:
(1) To increase freshwater resources by retarding the flow velocity
(2) To stabilize the water yield
(3) To solve regional disparities by localization

Expected effects of water resource development:
(1) Sustainable, systematic agricultural production and regional economic activities
(2) Geographical widening of agricultural production and other activities
(3) Restoration, settlement and expansion of vegetation

(1) Stabilization of the water yield

Since precipitation, namely the fallout of water to the land, is not steady, the water yield naturally changes with time. The changes are noticeable particularly in regions with clear division between the dry and rainy periods. From the viewpoint of water use, on the other hand, it is preferable that the water yield is maintained at a steady level so that water use is not affected by the amount of water available at each time point.

To bring the highly fluctuating water yield as close as possible to a steady state, is one of the major objectives of water resource development, since doing so will allow systematic and steady regional development.

(2) Solution to regional disparities in the water yield

Regional disparities found in the water yield are caused by the following regional factors:

- The rainfall distribution is not even.
- Water gathers in specific areas such as valleys.
- Accessibility to water resources varies.

Accessibility refers to the difficulty of accessing water sources, for example, the need to dig a deep well to access groundwater. There are many cases where accessibility to water resources is reflected in the locations of cities, communities and industrial centers; all these locations with a high water demand are concentrated in specific areas. On the other hand, activities such as agricultural production necessitate the use of water in wide areas.

As explained above, to localize water resources (now concentrating in specific areas), if necessary, in order to solve the problem of regional disparities, is another major objective of water resource development. This may consequently lead to water benefits and increased economic activities in wider areas.

(3) Settlement of vegetation

Vegetation growth, the foundation of all productive activities, supports a diverse range of biological activities. Although vegetation growth is influenced by many factors, many regions meet the requirements for the settlement of vegetation as long as the water supply is sufficient and steady. The same is true with agricultural production.

The effects expected from water resource development include the creation of steady-state net annual water yield to allow the settlement of vegetation in all seasons and the localization of water resources to allow the proliferation of vegetation. Similarly, water resource development is likely to provide greater stability for agricultural production activities over wide areas.

2.2 Functions of Hydraulic Structures

As explained in the preceding section, water resource development creates public benefits. This section reviews the functions of hydraulic structures used to provide such public benefits and classifies these hydraulic structures by function.

2.2.1 Storing Function

Storage facilities, comprised of structures and spaces that receive variable amounts of water inflow and adjust the amounts of water outflow or water to be taken out, provide an effective means of stabilizing the water yield. These facilities include surface dams, retarding basins and subsurface dams. The first two facilities have surface water storage space, while the third one has subsurface water storage space. These facilities can retard the velocity of water inflow and thus make it easier to capture water. This accordingly reduces dead outflow and increases the water yield.

2.2.2 Intake Function

Intake facilities provide a means of accessing water sources to capture water. Principal intake facilities are listed below.

- Intake of river water
  Headworks, intake weir and mountain stream intake works
- Intake of lake water
  Water gate
- Final closure
  Estuary weir
- Intake of groundwater
  Well and collecting well

2.2.3 Water Distribution Function

Water distribution facilities that link water sources with consumption places are referred to as channel works and provide an effective means of solving regional disparities in the water yield. If developed within a network, these facilities can achieve water benefits to wide areas.

2.3 Water Resource Development Options

Water resource development is based on the use, in various combinations, of facilities that fulfill functions explained in the previous section. Water resource development is largely classified into four categories based on, for example, water source locations:

(1) Surface water development
(2) Groundwater development
(3) Filtration
(4) Water conservation

Examples of facility combinations are shown below for each category.

2.3.1 Surface Water Development

(1) River (water source) → intake works → channel works → beneficiary area:
Natural water flow down from a water source to a beneficiary area

(2) River (water source) → intake works → channel works → storage reservoir and water storage tank (water source) → channel works → beneficiary area:
The pumping of water from a water source to a high elevation and from there the supply of water to a beneficiary area, or the installation of a storage reservoir to adjust water volume on the way to a beneficiary area

(3) Dam (water source) → intake works → channel works → beneficiary area:
Direct supply of water from a dam (water source) to a beneficiary area through a waterway

(4) Dam (water source) → river (water source) → intake works → channel works → beneficiary area:
The adjustment of the volume of water flow down a dam and the intake of water from a downstream headworks

(5) Dam (water source) → intake works → channel works → dam (water source) → intake works → channel works → beneficiary area:
The diversion of water to a large-capacity dam with a small catchment area from a water source in another catchment area

(6) River (water source) → retarding basin (water source) → intake works → channel works → beneficiary area:
The storage of flooding river water in a retarding basin

2.3.2 Groundwater Development

(1) Well (water source) → beneficiary area:
The installation of a well in a beneficiary area

(2) Well (water source) → channel works → beneficiary area:
The distribution of water from a well over wide areas

(3) Well (water source) → channel works → storage reservoir and water storage tank (water source) →

channel works → beneficiary area:

The pumping of water from a well to a higher elevation and from there the supply of water to a beneficiary area, or the installation of a storage reservoir on the way to a beneficiary area

(4) River (water source) → infiltrating ground surface → groundwater (water source) → well → beneficiary area:

Subsurface infiltration of river water to increase groundwater recharge and the intake of water downstream

(5) Subsurface dam (water source) → well → channel works → beneficiary area:

Damming and pumping of groundwater

(6) Subsurface dam (water source) → well → storage reservoir and water storage tank (water source) → channel works → beneficiary area:

The pumping of water from a subsurface dam to a higher elevation and from there the supply of water to a beneficiary area, or the installation of a storage reservoir on the way to a beneficiary area

(7) River (water source) → infiltrating ground surface → subsurface dam (water source) → well → channel works → beneficiary area:

The storage of water including infiltrated subsurface water in a subsurface dam

2.3.3 Filtration

Filtration refers to the removal of impurities for recycling of water. Related facilities are shown below.

- Wastewater treatment facility
- Seawater desalination facility

2.3.4 Water Conservation

Water conservation is designed to reduce dead flow or water waste during the course of water supply and use in order to increase the water yield. Water saved by water conservation can be used for applications or regions in which the water demand has only partially been met. The important points for water conservation are to prevent water leakage, develop water supply systems including the installation of water feed valves, and ensure thoroughness of water management.

2.4 Precautions during Development

Water resource development must be discussed and planned by the many individuals concerned based on appropriate information before it moves to the implementation stage. The matters that must be taken into consideration during these processes are summarized below.

2.4.1 Promotion of Participation of Concerned Individuals

Water is a fundamental resource circulating in the environment, indispensable for the maintenance of life on Earth. The role of water resource development, which was explained in Chapter 2, Section 1, can be fulfilled on the condition that facilities be constructed effectively and that they be managed and controlled properly. However, the use of the top-down approach is not preferable for facility management and water use control since the method is associated with the two problems described below.

- Residents in water-rich regions should naturally have advantages in terms of water use. However, the top-down method may severely reduce the rights of such residents and instead give priority to a larger number of urban residents.
- The top-down method may discourage the sense of ownership and instead encourage avoidance of responsibilities among beneficiaries. This may ultimately lead to frequent problems from the viewpoint of the maintenance of facility functions.

The basic concepts necessary for water resource development are presented below in order to provide an effective framework to ensure public benefits and the reflection of local priorities.

- The autonomy of residents and local governments must be fully respected. Problems that cannot be solved locally must be solved through cooperation of multiple local governments under the coordination of a higher administrative body.
- The role and limitation of authority of each administrative body (local, regional and central governments) must be clearly defined and fairness must be ensured.
- Regarding the public benefits of water resource development, full understanding by the residents must be established.
- The recognition by beneficiaries that the responsibility of facility maintenance and management belongs to them must be established.
- Various procedures from plan writing to facility maintenance and operation for specific water resource development must follow democratic principles.

2.4.2 Information Sharing

When carrying out specific activities for a development project approved through discussions participated in by concerned individuals, it is important that all the individuals, not only beneficiaries but also those susceptible to direct or indirect disadvantages, share various information regarding the development project in a timely manner. Such information must be provided by the administrative body concerned. The individuals concerned include the residents in regions likely to encounter environmental changes as a result of facility construction.

Information that should be shared includes highly technical subject matter. With regard to the development method, it is essential that assertive and coercive proposals be excluded, but several options must be presented for examination. Following is a list of the information that should be shared.

(1) Water source development methods

(2) Water source locations

(3) Facilities that should be constructed

(4) Level of facilities

(5) Water yields

(6) Water supply and distribution methods

(7) Project costs

(8) Environmental changes

Changes expected immediately after construction

Long-term changes (Changes that occur with time)

Countermeasures

(9) Water utilization plans

(10) Facility operation methods

Labor relations

Consumable material and energy

Funds

(11) Facility maintenance and management plans

Regular maintenance and inspection methods

Anticipated failures and their causes

Measures taken against failures

Repair costs

Service life

Renewal costs

(12) Functional maintenance plans

(13) Water quality management plans

2.4.3 Importance of Functional Maintenance

Water resource development is a foundation for all regional development activities and the most labor- and cost-intensive aspect is the construction of facilities. Nonetheless, water resource development does not end with the construction of facilities, but effective utilization of facilities following construction is important. The facilities constructed under development projects come to have significance only when they can withstand long-term use in sound functional condition.

Over time, facilities naturally suffer from deterioration and degradation or loss of function such as failures. In anticipation of such situations, prior examination of measures is needed. Environment changes anticipated from the installation and operation of facilities must also be forecast. Briefly reviewed below are the environmental changes anticipated from the installation and operation of facilities as well as the measures to maintain them in sound functional condition.

(1) Water distribution facilities (channel works)

<table>
<tr><th></th><th>Open channel
(openwork and lining)</th><th>Waterway tunnel</th><th>Pipe line</th></tr>
<tr><td>Installation location and method</td><td>A kind of waterway that carries water from the water source to the beneficiary area through natural flow. Classified into two types: the openwork – a ditch-like channel – and the lined waterway with paved surface to prevent erosion and water leakage.</td><td>Used when the water source and beneficiary area are separated by a ridge because the use of the open channel that carries water through natural flow alone lengthens the route.</td><td>A pressure pipe waterway that can be installed under various topographic conditions to carry water</td></tr>
<tr><td colspan="4">(Environmental changes)
Changes in biota and various environments in destinations of water supply routes (including the areas surrounding the open channel route)</td></tr>
<tr><td colspan="4">(Precautions during operation)
River discharge if the water source is the river and groundwater level if the water source is groundwater
Water leakage and subsurface infiltration
Adjustment of the flow velocity, flow rate and supply amount</td></tr>
<tr><td colspan="4">(Functional maintenance plans)
Waste accumulation
Facility deterioration and damage
↓
Waste removal
Facility inspection and repair</td></tr>
</table>

(2) Storage facilities (source)

	Surface dam	Retarding basin	Subsurface dam
Installation location and method	Uses the slopes on both sides of the river (valley) and the cut-off wall installed to cut off the valley Installed in effective locations based on the calculation of the relationship between the cut-off area and storage	Constructed by digging into the riverbed or the ground not far from the river This structure is not designed to cut off the river flow. Installation locations are limited to alluvial plains and other gentle slopes	Used to cut off the subsurface valley by installing the subsurface cut-off wall * Subsurface valley: A location where a poorly permeable soil layer (hereafter referred to as the hydraulic basement) is covered by a porous soil layer and the hydraulic basement is shaped like a valley
Environmental changes	Increased upstream water level Widening of water-filled areas Cutting off of water flow ↓ Loss of land Rise of groundwater level in the slope Changes in biota in water Obstruction of the migration and interaction of aquatic life such as fish, and the fragmentation of habitats Changes in the environment of construction-related sites such as quarries for cut-off wall material and stockyards for surplus soil	Widening of water-filled areas ↓ Loss of land Changes in biota in water Changes in the environment of construction-related sites such as stockyards for surplus soil	Changes in the groundwater level ↓ No particular changes Changes in the environment of construction-related sites such as quarries for cut-off wall material and stockyards for surplus soil
Precautions during operation	Slope stability in water-filled areas Eutrophication of reservoir water due to the elution of organic substances Water leakage Evaporation Adjustment of the river discharge	Eutrophication of reservoir water due to the elution of organic substances Evaporation	Increased flooding Depletion of downstream springs Salinity of groundwater in coastal regions
Functional maintenance plan	Accumulation of sediment and nutritive substances, and reduced storage space due to sedimentary accumulation Deterioration and damage to the cut-off wall ↓ Dredging of the reservoir bottom Measures to prevent collapses of the mountain slope Inspection and repair of the cut-off wall	Inflow of sediment and resultant reduction of storage space ↓ Dredging	Semi-permanent functions

(3) Storage facilities (transit point)

	Storage reservoir	Water storage tank (tank)
Installation location and method	Classified into two types: one in which a cut-off wall is constructed in a natural valley and the other in which a cut-off wall is constructed by digging into the ground Exposure to the open air allows the storage of natural inflow such as rainfall.	Classified into two types: one that is installed on the ground and the other that is constructed by digging into the ground. Certain standards apply to the form and volume of the container. To prevent the entry of impurities, the tank often comes with a ceiling or cover.
Environmental changes	Increased water level Water filling ↓ Loss of land Changes in biota in water Changes in the environment of construction-related sites such as stockyards for surplus soil	Land occupancy by structures
	(Precautions during operation) Eutrophication of reservoir water due to the elution of organic substances Water leakage Evaporation	(Precautions during operation) Water leakage
Functional maintenance plan	Accumulation of sludge Facility deterioration and damage ↓ Dredging Facility inspection and repair	Waste accumulation Facility deterioration and damage ↓ Waste removal Facility inspection and repair

(4) Groundwater aquifer charging facilities

	Open channel and aqueduct	Infiltrating ground surface	Recharge well
Installation location and method	Infiltration of water into subsurface soil by means of ditching (linear) on the ground surface to collect inflow. Installed on alluvial plains, including alluvial fans that allow subsurface infiltration.	Infiltration of water into subsurface soil by means of digging into the riverbed or the ground near the river to collect inflow. Infiltrating ground surface also functions as flood control.	A kind of well used to charge surface water, which then infiltrates into the subsurface.
(Environmental changes) Reduced river discharge Groundwater distribution in the downstream catchment area			
(Functional maintenance plans) Reduced infiltration capacity due, for example, to clogging ↓ Closing and installation of a recharge well Recovery of the functions of the open channel, aqueduct and infiltrating ground surface by dredging			

2.5 Characteristics of Subsurface dam Development

2.5.1 Merits

(1) No submergence

Normally, with no submergence of the reservoir area involved, subsurface dam development does not interfere with current land use. Since it has only minimal social impact (for example, it does not entail the relocation of residents), its impact on the ecosystem is only minimal.

(2) No loss of stored water from evaporation

Since the subsurface dam suffers virtually no loss of stored water from evaporation, it is more advantageous than the surface dam in dry regions.

(3) Semi-permanent maintenance of functions

The absence of surface structures ensures no obstruction to the circulation of materials such as sediment and nutrient salt. It also ensures no obstruction to the migration and interaction of living creatures. Unlike the surface dam, it does not suffer from a reduction of storage space due to sedimentary accumulation. Since the cut-off wall, buried underground, is not likely to corrode or deteriorate, the function of the subsurface dam is almost permanently maintained.

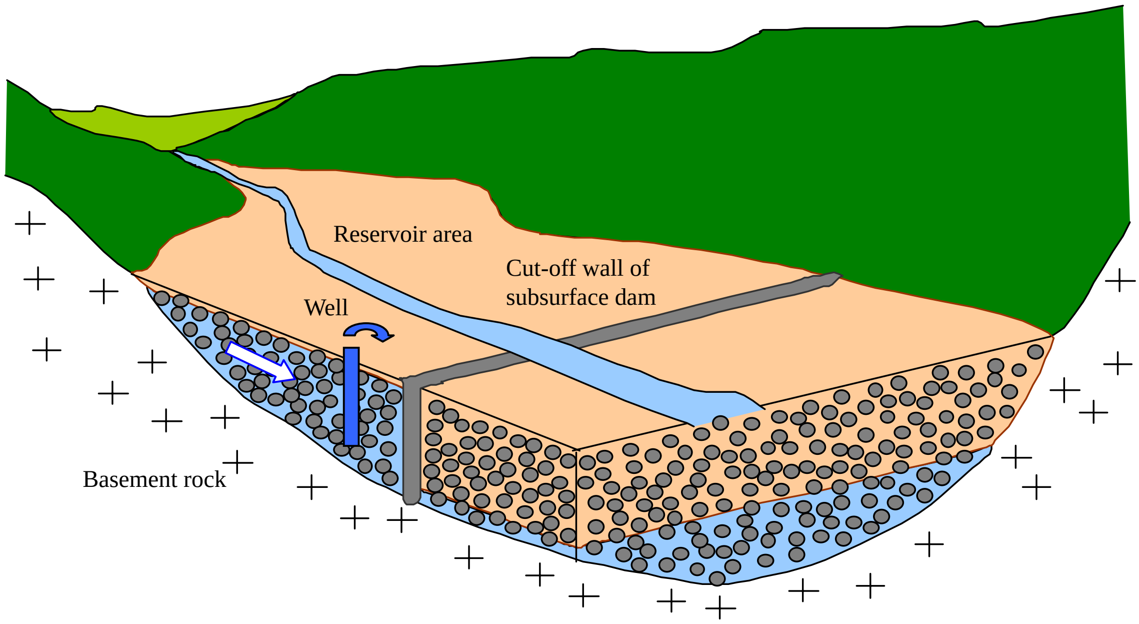
2.5.2 Subsurface dam Types

Subsurface dams are largely classified into two types.

(1) Afflux dam

The afflux dam is designed to store groundwater. The reservoir, which dams up groundwater and regulates its discharge, accordingly increases the groundwater level and allows stable intake of groundwater.

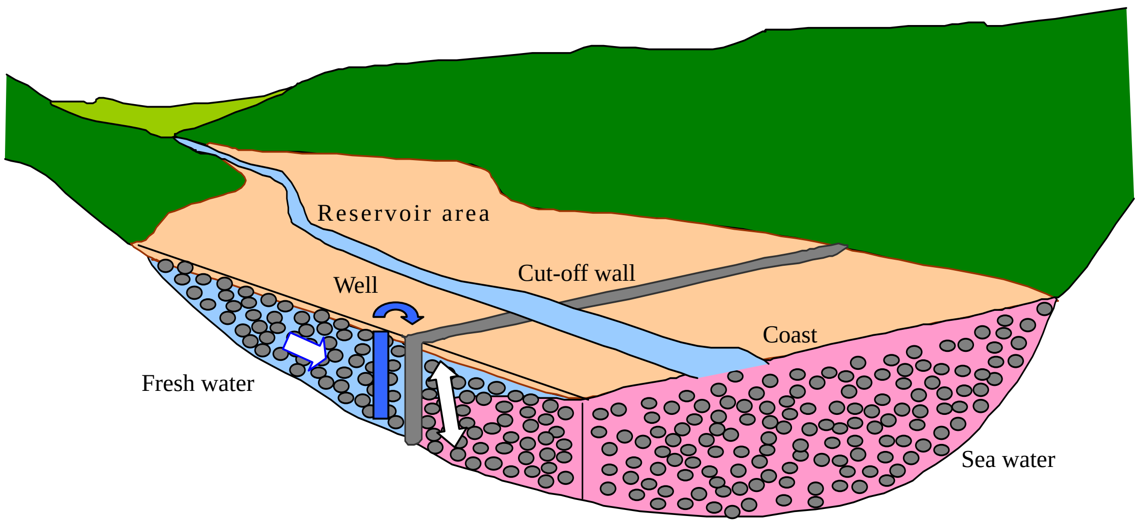
Figure 2.5.1 Conceptual Diagram of the Subsurface dam (Afflux dam)



(2) Saltwater infiltration prevention type

The saltwater infiltration prevention dam is designed to prevent saltwater from infiltrating groundwater and to protect available water resources. Fluctuations of the groundwater level cause a vertical shift of the border between sea water and fresh water. Nonetheless, the reservoir, on the landward side of the cut-off wall, unconditionally allows groundwater pumping and the resultant adjustment of the groundwater level. Like the afflux dam, the saltwater infiltration prevention dam holds groundwater back and regulates its discharge.

Figure 2.5.2 Conceptual Diagram of the Subsurface dam (Saltwater Infiltration Prevention dam)



2.5.3 Problems

Circumstances deem it necessary to start construction based only on prior information (generally far from accurate) about surface properties. This imposes technical risks regarding whether or not the construction work can actually be completed. To improve the accuracy of calculation of the storage capacity and the construction area of the cut-off wall, a considerable amount of surveying is required.

Since water is stored in surface spaces, the gross reservoir capacity is small relative to the scale of construction. A long spell of dry weather with no groundwater recharge will necessitate a reduction in the amount of water use. Regions under such meteorological conditions have only limited areas that can benefit from the subsurface dam. To achieve success in development projects, certain conditions must be fulfilled; for example, a large gross reservoir capacity must be ensured despite a small dam sectional area. However, regions that can satisfy such a requirement are rare (although regions that can meet the requirements for surface dam development are many). This special circumstance is the very reason why subsurface dam projects are difficult.

Strict control of subsurface dam water is difficult because stealing water is easy simply by digging a well. To prevent such practice, restrictions must be placed on land use and economic activities in the subsurface dam reservoir area, and concerned parties must develop morals to protect the water resource.

2.6 Development Steps

To increase the public benefits of subsurface dam projects, it is important to produce a plan that promises benefits to wide areas. It is necessary to examine methods that use water made available by subsurface dam construction together with water from existing water sources to vitalize wider areas. To achieve synergy effects, it is important to concurrently develop a subsurface dam and construct a waterway to improve the water supply network.

2.6.1 Flow of Water Resource Development

With a goal of integrating the subsurface dam in the wide-area water supply network, the following section summarizes the flow of water resource development.

(1) Basic study (Basic Study: hereafter referred to as B/S)

The B/S is designed to examine, while considering regional natural conditions, the possibility of large-scale water source development such as the construction of subsurface dams, and prepare data necessary for producing a realistic M/P.

(2) Drafting of the comprehensive basic plan for regional development (Master Plan: hereafter referred to as M/P)

The M/P is a general wide-area plan that incorporates consideration for the water demand (water utilization plan) and the economic and financial state in the target region. The plan also uses the water source development method suggested by the B/S.

(3) Feasibility Study (Feasibility Study: hereafter referred to as F/S)

The F/S is designed to form consensus among concerned individuals, review the M/P based on the consensus and finalize individual project plans. It is particularly important during the F/S to carefully examine the sustainability of each development project.

(4) Detailed design (Detail Design: hereafter referred to as D/D)

The D/D is designed to create detailed designs prior to construction.

(5) Implementation of the project

Bilateral or multilateral economic and technical cooperation

(6) Maintenance and management

In consideration of the information that should be shared shown in 2.4.2, specific matters that must be examined in each stage from B/S to D/D are shown in Table 2.6.1.

Table 2.6.1 Development Steps and Matters for Examination

Study Stage	B/S	M/P	F/S	D/D
(1) Water source development methods	○	○	○	
(2) Water source locations	○	○	○	○
(3) Facilities that should be constructed	○	○	○	○
(4) Level of facilities	○	○	○	○
(5) Water yields	○	○	○	
(6) Water supply and distribution methods		○	○	
(7) Project costs		○	○	○
(8) Environmental changes		○	○	
(9) Water utilization plans		○	○	(○)
(10) Facility operation methods			○	(○)
(11) Facility maintenance and management plans			○	(○)
(12) Functional maintenance plans			○	(○)
(13) Water quality management plans			○	(○)

(○) means that, if necessary, the F/S must be reviewed.

2.6.2 Scope of Application of the Technical Reference

The correspondence between the matters for examination in each process of subsurface dam development and how this technical reference is organized is shown in the table below.

Table 2.6.2 Scope of Application of the Technical Reference

Study Stage	B/S	M/P	F/S	D/D
(1) Water source development methods	Chapter 3 Chapter 4	 Same as left	 Same as left	
(2) Water source locations	Chapter 3 Chapter 4	 Same as left	 Same as left	 Same as left
(3) Facilities that should be constructed	Chapter 4 Chapter 4	Same as left Same as left	Same as left Same as left	Chapter 5 Chapter 5
(4) Level of facilities	Chapter 4	Same as left	Same as left	
(5) Water yields		Chapter 4	Same as left	
(6) Water supply and distribution methods				
(7) Project costs		Chapter 4	Same as left	Same as left
(8) Environmental changes		Chapter 2	Chapter 4	
(9) Water utilization plans		Chapter 3	Chapter 4	
(10) Facility operation methods			Chapter 7	
(11) Facility maintenance and management plans			Chapter 7	
(12) Functional maintenance plans			Chapter 7	
(13) Water quality management plans			Chapter 7	

Chapter 3 Preliminary Survey

This chapter introduces various groundwater development and conservation measures and assesses the propriety of each measure. This chapter also examines the significance of the subsurface dam in groundwater development and presents selection methods for suitable sites for subsurface dam development. Finally, the results of on-site surveys conducted are provided.

3.1 Basic Concepts Underlying the Selection of the Development Method

3.1.1 Motives for Development and Problem Factors

The preceding chapter described the role of water resource development and functions of hydraulic structures to be developed. Motives for development and problem factors are summarized below. It is recommended that from these viewpoints, problems be identified and facility combinations be examined to solve the problems.

Table 3.1.1 Motives for Development and Measures to Solve Problems

Motive for Development	Measure	Method
Time-based variations of water resources	Creation of steady-state conditions	Installation of storage facilities
Regional disparities in water resources	Resource distribution	Construction of distribution channel

All regions potentially have motives for water resource development. However, before any actions are actually taken, careful examination must be made particularly regarding the installation of storage facilities, as it is associated with the problem factors listed below. The Basic Study (B/S) compares the problem factors and positive effects anticipated from development, and identifies the feasibility and necessity of development.

Table 3.1.2 Problem Factors for Storage Facility Development

Facility Type	Problem Factor
Surface dam	* Relatively short functional service life and difficulty of functional maintenance * Problems associated with substance circulation * Project cost * Maintenance and management cost
Subsurface dam	* Rarity of suitable development sites * Project cost

3.1.2 Priority of Examination

Before examining storage facilities, the priority of examination should be given to a solution combining various methods, as it becomes the second-best measure when large-scale development such as the construction of storage facilities must be given up. As shown by the examples in 2.3 Water Resource Development Options in the preceding chapter, several development method options that do not use the surface dam or subsurface dam are still available.

(1) Surface water development (excluding dams)

What comes first in the priority of examination is surface water development. Typical surface water development includes the installation of intake works in a constantly flowing river and the distribution of water from the intake works through the waterway. This type of development is effective in that water flowing in the river can be distributed over wide areas and at the same time the impact of fluctuations of the flow rate over time can be mitigated and spread out. It is also effective to use the complementary measure of installing small-scale storage reservoirs and water storage tanks.

(2) Groundwater development (excluding subsurface dams)

If no constantly flowing rivers are found, what should be examined next is groundwater development. Groundwater that flows more slowly than surface water is regarded as a type of naturally stored water. Since groundwater is circulating, groundwater development within the limit not exceeding the recharge would be theoretically sustainable. The groundwater development method will be explained later.

(3) Dam development

The examination of the development of a surface dam or subsurface dam (both are structures that cut off rivers) must be preceded by the examination of (1) and (2) above. If dam development is selected, however, it must be ensured that wide areas enjoy the benefits of the development, considering the risk involved. As already explained in 2.6 Development Steps, it is important not to consider water source development as something separate but to consider it within the framework of a wide-area water supply network that includes areas not directly benefiting from the development.

(4) Filtration and water conservation

Major issues regarding filtration and water conservation are how to maintain and manage facilities and how to meet the water requirement. Mainly from the economic perspective, a comparison of these measures with dam development will be required. However, depending on circumstances, filtration and water conservation may come higher on the priority list than dam development.

3.2 Groundwater Development and Conservation Measures

3.2.1 State of Groundwater Distribution

Groundwater, which is found filling subsurface voids, is largely classified into two types based on how it fills the voids: stratum water and fissure water. Stratum water and fissure water refer respectively to groundwater present between sediment particles and groundwater present in fissures and fractures in the bedrock. Table 3.2.1 summarizes the state of groundwater distribution with reference to soil types.

Table 3.2.1 Soil Types and Hydraulic Conditions

Groundwater Category	Soil Type		Effective Porosity (Approximate %)
Stratum water	Quaternary Period sediments	Gravel layer Sand layer Mud layer	15 to 20 30 5 to 10
	Tertiary Period sedimentary rocks	Sandstone and conglomerate	5 to 20
	Volcanic breccia		5 to 20
Fissure water	Porous limestone	(Eluvial hole)	10 to 25
	Weathered rock		5 to 20
	Fault fractures		5 to 20
	Igneous rocks	Cooling joints and lava tubes (Shearing fissures)	1 to 5
	Metamorphic rocks and other		1 to 5

A larger effective porosity is a sign of a more productive aquifer. The most productive aquifers are the Quaternary Period gravel layer and sand layer. These sediments are found in low elevation areas and riverside areas such as alluvial plains, alluvial fans, diluvial plateaus and ravine plains, all of which are susceptible to long-term sea level changes. Generally, these aquifers increase in thickness and width with increased proximity to the sea. In coastal regions, impermeable layers (e.g. clay) are often found causing vertical fragmentation of the aquifer.

Undulated areas and inland plateaus are generally considered to have formed before the Tertiary Period. The Quaternary layers are poorly developed even in riverside areas. Groundwater is often found in the form of fissure water in weathered layers near the surface or in the bedrock below the weathered layers. Limestone, made of calcium carbonate that dissolves into groundwater and forms hollows and voids, helps form a productive aquifer.

Since the groundwater table is more gently contoured than the actual landform, its contour lines are more widely spaced. In regions of relatively low elevation (such as valleys), ground surface and groundwater table generally approach each other. Groundwater flows across contour lines of the groundwater level.

3.2.2 Specific Development and Conservation Measures

(1) Intake of yet-to-be developed deep groundwater

The digging of deep wells is one of the measures to improve access to water sources. Deep wells enable access to water running deep underground. Although the recharge water should not entirely be pumped, the amount of water intake can be increased on a sustainable basis. Sustainable basis means that a reduction of the groundwater level will not occur over time. To ensure continuous water intake throughout the year, it is important to ensure sufficient water depth, while considering the minimum annual water level and the water level drop from pumping.

(2) Introduction of innovative water intake methods

To reduce wasted runoff of groundwater, it is essential to pump small amounts of water from wide areas. Increasing the number of water intake locations and reducing intake intensity (the amount of water intake per unit time) without depending on a single water source can prevent a sudden lowering of the water level as a result of pumping.

In regions with concerns over saltwater infiltration to groundwater, methods such as the installation of a collecting well for intensive intake of shallow groundwater may be introduced.

(3) Increase of groundwater recharge

It is important to construct a balancing reservoir in a relatively high location of an aquifer holding area to infiltrate flooding river water and increase groundwater recharge. Subsurface infiltration is most significant in that it can retard runoff. Water irrigation to farmland in upper and middle river reaches may also result in an increase in groundwater recharge. Water infiltrated into the subsurface can be recycled in lower river reaches.
Another view from a different angle is also found; promoting the use of groundwater to reduce the groundwater level will enhance subsurface infiltration, increase the entry of water into voids during flooding and consequently help flood control.

(4) Use of another water source

If the use of groundwater is currently excessive and the groundwater source is not sustainable even if measures (1) to (3) above are taken, the use of groundwater must be limited in order to protect the groundwater source in the region. If circumstances make it necessary to reduce the amount of groundwater use, another water source must be used. The requirements for the replacement are that its potential water yield is much greater than the current water yield and that it is located nearby.

Alluvial plains in coastal regions may suffer from ground subsidence caused by groundwater pumping. If such a problem is already present, the use of groundwater must be reduced. Since these coastal regions are usually characterized by large volumes of water use and drainage, it is worth considering seawater desalination and sewage treatment as development options.

(5) Subsurface dam development

When the examination of measures to develop and protect groundwater as explained in (1) to (4) above has determined that these measures would not ensure the supply of the required amount of water or that these measures would not be economical, subsurface dam development must be examined. However, it must be remembered that even so, the target regions may not satisfy the requirements for subsurface dam development. It will be necessary, therefore, to separately examine the issue of selecting suitable sites for subsurface dam development. The matters for consideration regarding the selection of suitable sites are described in the following section.

3.3 Requirements of Suitable Sites for Subsurface dam Development

3.3.1 Geographical Characteristics

The requirements that must be satisfied by the regions (hereafter referred to as the suitable subsurface dam sites) worth being considered for subsurface dam development are summarized below. The special circumstances surrounding subsurface dam development are attributed to the fact that regions that can satisfy all three requirements below are rare.

(1) Necessity: Large seasonal fluctuations in the groundwater level (Dam type)

The area holding quality groundwater is receding (Saltwater infiltration prevention type)

(2) Functionality: Ample storage space

(3) Efficiency: Reduction of the cut-off area to a minimum

The construction of a subsurface dam generally requires cutting off where an subsurface valley is covered by an aquifer. Subsurface valleys are usually formed where the ground is undulating. As in the case of surface dams, by tracing subsurface valleys, effective sites for subsurface dam development can be easily found.

On the other hand, if a major emphasis is placed on functionality, sites with thick aquifers or sites with thin but wide (long) aquifers are ideal. Soil types with large porosity, which can hold large volumes of water, include the alluvial gravel layer, limestone and volcanic rocks. However, subsurface valleys must be comprised of uniformly poorly permeable soil.

The topographical characteristics of the sites with productive aquifers that can meet the requirements for functionality (adequate reservoir capacity) and efficiency (the presence of an subsurface valley) are discussed below.

Orogenic zone (Island areas and continental borderlands)

- Drowned valley
- Top of alluvial fan (Contact point between the mountain and alluvial plain)
- Karst (Limestone plateau)

Stabilized continent (Mid-continent)

- Wadi
- Karst

The suitable sites for subsurface dam development must have topographical characteristics described above and must be located in regions considered in need of water source development. The topographic properties suitable for the development of each type of subsurface dam are shown below. Since the drowned valley in the orogenic zone has a quite steady groundwater level, which is close to the sea water level and is often close to the ground surface, the development target is the saltwater infiltration prevention dam.

Table 3.3.1 Topographic Proprieties Suitable for Subsurface dam Development

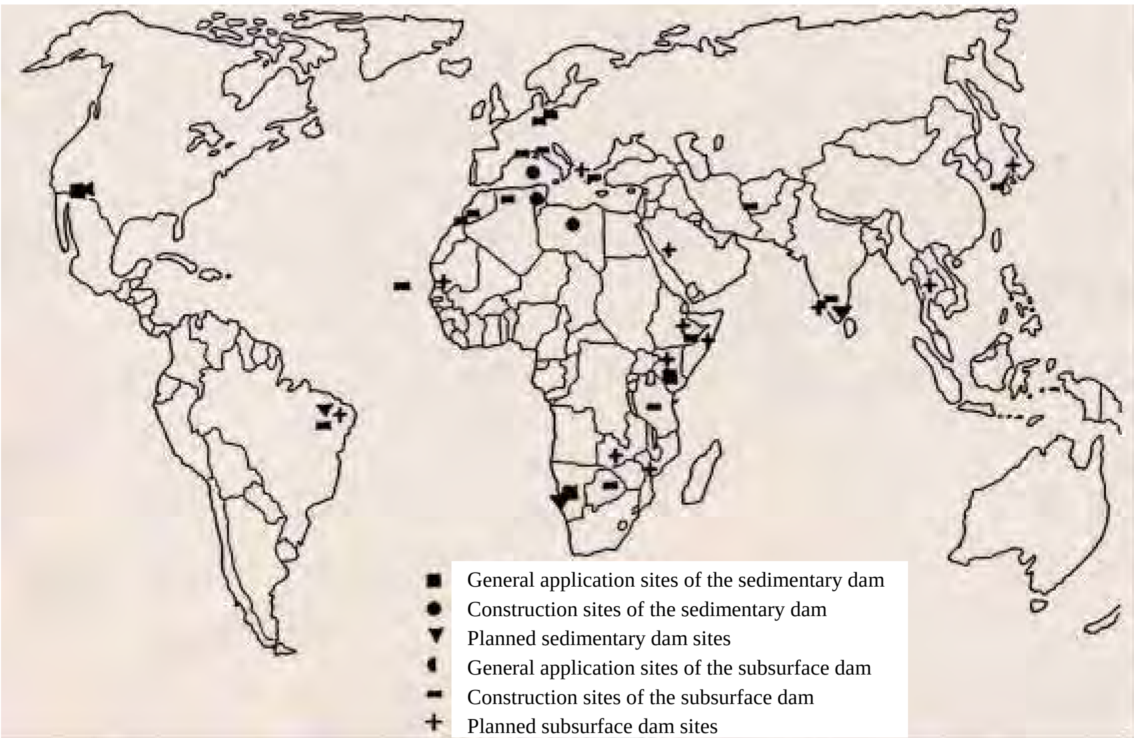
Topographical Characteristics		Dam Type	Saltwater Infiltration Prevention Type
Orogenic zone	Drowned valley		○
	Top of alluvial fan	○	
	Karst	○	○
Stabilized continent	Wadi	○	
	Karst	○	

3.3.2 Distribution of Groundwater dams around the World

Figure 3.3.1 shows the locations of known groundwater dams around the world as of 1986. Groundwater dams are classified into two types: the subsurface dam, which has a cut-off wall constructed underground, and the sedimentary dam, which has a cut-off wall projecting above the surface to dam up sediment and keep water in the sediment.

Of these known groundwater dams, 70% are located in dry and semi-arid areas such as desert, savannah and step areas. Of these dams, 30% are sedimentary dams, an indication that it is important to prevent evaporation. While Europe and Northwest Africa have large-scale groundwater dams, other areas have smaller dams.

Figure 3.3.1 Locations of Groundwater dams around the World (Hanson & Nilsson, 1986)



3.3.3 Distribution of Subsurface dams in Japan

There is only a short history and few examples of subsurface dam development projects in Japan. However, a clear trend is already observed in regional distribution: for example, the projects are concentrated in small islands and narrow peninsulas (Figure 3.3.2). Large-scale subsurface dams with a gross reservoir capacity exceeding 1 million m^3 are concentrated in areas with limestone soils on southwestern islands.

All these regions meet the conditions shown in Table 3.3.1, and at the same time, share common geographical characteristics of being isolated by the sea or mountains, which make water transport from water-rich regions difficult. In these regions under difficult geographical conditions, therefore, subsurface dam development is the only option available. In regions of relatively stable rainfall throughout the year, sites suitable for subsurface dam development may be limited to areas with such geographical characteristics.

The design flow shown in Table 3.3.2 and Table 3.3.3 refers to the amount of water available, which is set in consideration of the rainfall pattern in each region. The design flow (m^3/day), therefore, varies depending on the size of the catchment area, annual amount of rainfall, number of days of dry weather, and other factors, even if the gross reservoir capacity is the same. A rough estimate of the design flow can be made using the two equations below (a lower value obtained from one of the two equations is the design flow.)

- Size of the catchment area × Mean annual rainfall × (0.1 to 0.5) ÷ (365)
  When the gross reservoir capacity is significantly large relative to the total amount of water that infiltrated the catchment area
- Gross reservoir capacity ÷ The maximum number of days of continuous dry weather
  When the gross reservoir capacity is small and a considerable amount of overflow is expected during the rainy season

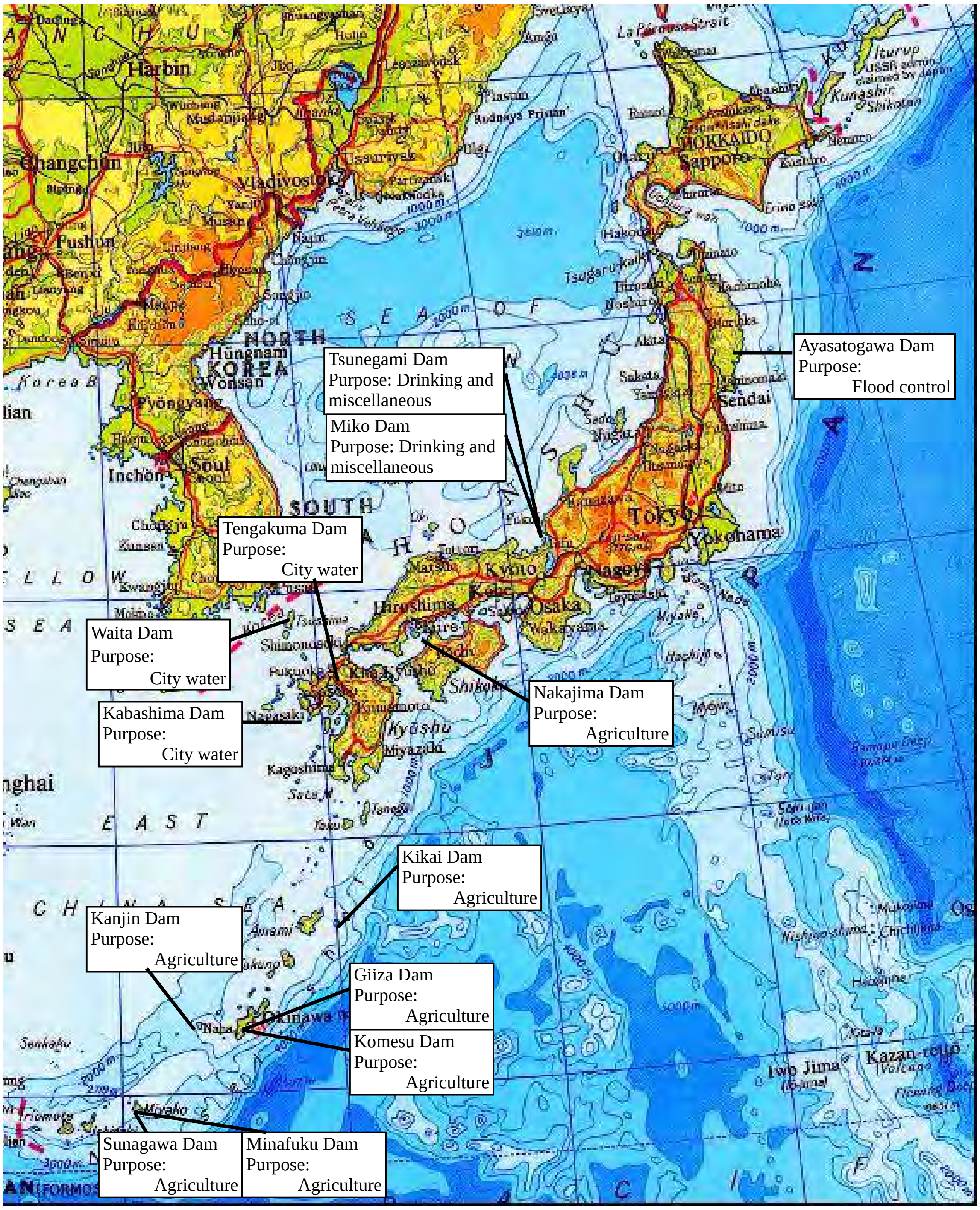
Table 3.3.2 Examples of Subsurface dam Construction (in Drowned Valleys and Alluvial Fans)

Name of Subsurface dam	Location		Year of Construction	Dam Height (m)	Dam Length (m)	Gross Reservoir Capacity (m^3)	Design Flow (m^3/day)
	Prefecture	Municipality					
Kabashima	Nagasaki	Nomozaki	1974	24.8	59	9,340	300
Tsunegami	Fukui	Mikata	1982-1984	18.5	202	73,000	400
Tengakuma	Fukuoka	Umi	1987-1988	12.5	129	17,500	900
Waita	Nagasaki	Toyotama	1991-1992	7.5	105	12,000	280
Nakajima	Ehime	Nakajima	1991-1992	26.1	87	27,000	500
Ayasatogawa	Iwate	Sanriku	1991	4.2	120	30,000	
Miko	Fukui	Mikata	1996	39.3	196	23,000	460

Table 3.3.3 Examples of Subsurface dam Construction (in Limestone Soil Areas)

Name of Subsurface dam	Location		Year of Construction	Dam Height (m)	Dam Length (m)	Gross Reservoir Capacity (m^3)	Design Flow (m^3/day)
	Prefecture	Municipality					
Minafuku	Okinawa	Gusukube	1979	16.5	500	720,000	7,000
Sunagawa	Okinawa	Gusukube	1987-1994	50	1,677	9,500,000	24,000
Fukusato	Okinawa	Gusukube	1993-2000	27	1,790	10,500,000	30,000
Kikai	Kagoshima	Kikai	1993-2002	36	2,190	1,681,000	
Komesu	Okinawa	Itoman	1993-2003	80	2,489	3,457,000	8,900
Giiza	Okinawa	Gushikami	1998-2003	51	955	389,000	1,200
Kanjin	Okinawa	Gushikawa	1996-2003	52	1,088	1,580,000	

Figure 3.3.2 Distribution of Subsurface dams in Japan



3.4 Flow of Surveys for the Selection of Suitable Sites

Before preparing an M/P (See 2.6.1), a decision must be made regarding whether it is appropriate to include subsurface dam development as an option, in order to eliminate time waste and improve efficiency during the surveys that follow. Even when a project is considered premature, it is important to prepare comprehensive data on subsurface dam development as a matter for consideration on a national level in anticipation of a rise in demand in future. The following section presents methods for selecting suitable sites for subsurface dam development.

3.4.1 Hydrological and Geological Surveys

The surveys start with rough extraction of a relatively large number of candidate sites for subsurface dam development from wide areas based on natural conditions. The criteria are whether the three requirements (necessity, functionality and efficiency) described in 3.3.1 are met. The details of the surveys are below.

(1) Collection and analysis of existing topographical and geological data

From the viewpoints of functionality and efficiency, whether or not each candidate site has suitable geographical characteristics must be checked. The data that must be collected includes topographic maps (on a scale of approximately 1 to 200,000), geological maps (on a scale of approximately 1 to 200,000) and aerial photographs. The analysis of aerial photographs may help in estimating the subsurface valley shape.

(2) Collection and analysis of meteorological and hydrological data

This process is carried out in order to confirm the necessity of subsurface dam development. The data that must be collected includes the rainfall, river discharge, groundwater level and water quality. The collection of only available data is required (preferably for the past 10 years at least). The targets of analysis are groundwater level fluctuations (seasonal and yearly) and water quality deterioration.

3.4.2 Examination of Priority

The districts extracted above must be prioritized based on development potentials. The reference criteria used here are 2.1.6 Objectives of Water Resource Development and 3.1.2 Priority of Examination.

(1) Farming and vegetation surveys

Based on the general knowledge learned about planting patterns of local agriculture, the possibility of revitalizing agricultural production must be examined, assuming that water resource is available. This process is designed to confirm whether or not development has any significance from the point of view of public benefit (as explained in 2.1.6). The data that must be collected includes existing survey reports, agricultural statistics and vegetation maps.

(2) Understanding water use and land use patterns

The planar distribution of water use must be determined. Then, while considering the locational relationship between the beneficiary area and water source, various water resource development methods must be compared and examined (as explained in 3.1.2). The data that must be collected includes statistics regarding water and land use, and drawings and reports concerning water resource development projects (past and future projects). The meteorological and hydrological data collected earlier must also be used as reference.

(3) Site reconnaissance

Site reconnaissance must be carried out if (1) and (2) need to be supplemented.

Table 3.4.1 Flow of Surveys for the Selection of Suitable Sites

Matter for Examination	Details	How to Obtain Data
● **Extraction of suitable development sites**	**Hydrological and geological surveys**	
Extraction of sites with geographical characteristics suited for subsurface dam development (Table 3.3.1)	(1) Topographic and geological data Topographic maps, geological maps and aerial photographs	Purchase of data issued and supervised by a government bureau that manages geographical information.
Confirmation of the necessity of development (seasonal and yearly changes in the aqueous environment)	(2) Meteorological and hydrological data Rainfall, river discharge, groundwater level and water quality	Purchase of statistics issued by a government bureau that manages geographical information. Acquisition of reports produced by a government bureau that manages water resources. Acquisition of data from meteorological stations.
● **Development potentials**	**Examination of priority**	
Identification of the possibility of agricultural revitalization and the significance of development	(1) Farming and vegetation surveys Agricultural statistics, vegetation maps and soil charts	Purchase of statistics and reports issued by a local administrative agency. Purchase of drawings issued and supervised by a government bureau that manages geographical information.
Comparative examination of water source development methods	(2) Water use and land use surveys Water use statistics and land use maps	Acquisition of statistics and reports issued by a government bureau that manages water resources. Purchase of drawings issued and supervised by a government bureau that manages geographical information.
	(3) Site reconnaissance	Site inspection Acquisition of reports and data from other local agencies as supplementary data.

3.5 Examples of Surveys in Indonesia

The group of islands in the eastern part of Indonesia, with clear division between dry and rainy periods, is susceptible to large seasonal changes in the amount of rainfall. As the islands have a small land area, they suffer from poor water retentivity. These circumstances led to increased expectations for water resource development that includes the construction of subsurface dams as well as storage facilities.

Therefore, based on extensive consideration of the results of 3.4.1 Hydrological and Geological Surveys, an attempt was made in this region to select candidate sites for subsurface dam development. Additionally, in the course of examining the possibility of other water source development methods, the irrigation system in place in the target region was examined for their advantages.

3.5.1 Traditional Irrigation System on Bali

Bali is an island relatively long from east to west; 150 km long from east to west and a maximum of 80 km long from south to north. The amount of rainfall varies widely between regions on the island, and it also fluctuates widely on a yearly basis even at the same location. However, one thing is common: 90% of the annual rainfall is experienced during the rainy period of November to April.

Table 3.5.1 Monthly Rainfall in Denpasar, Bali (Unit: mm)

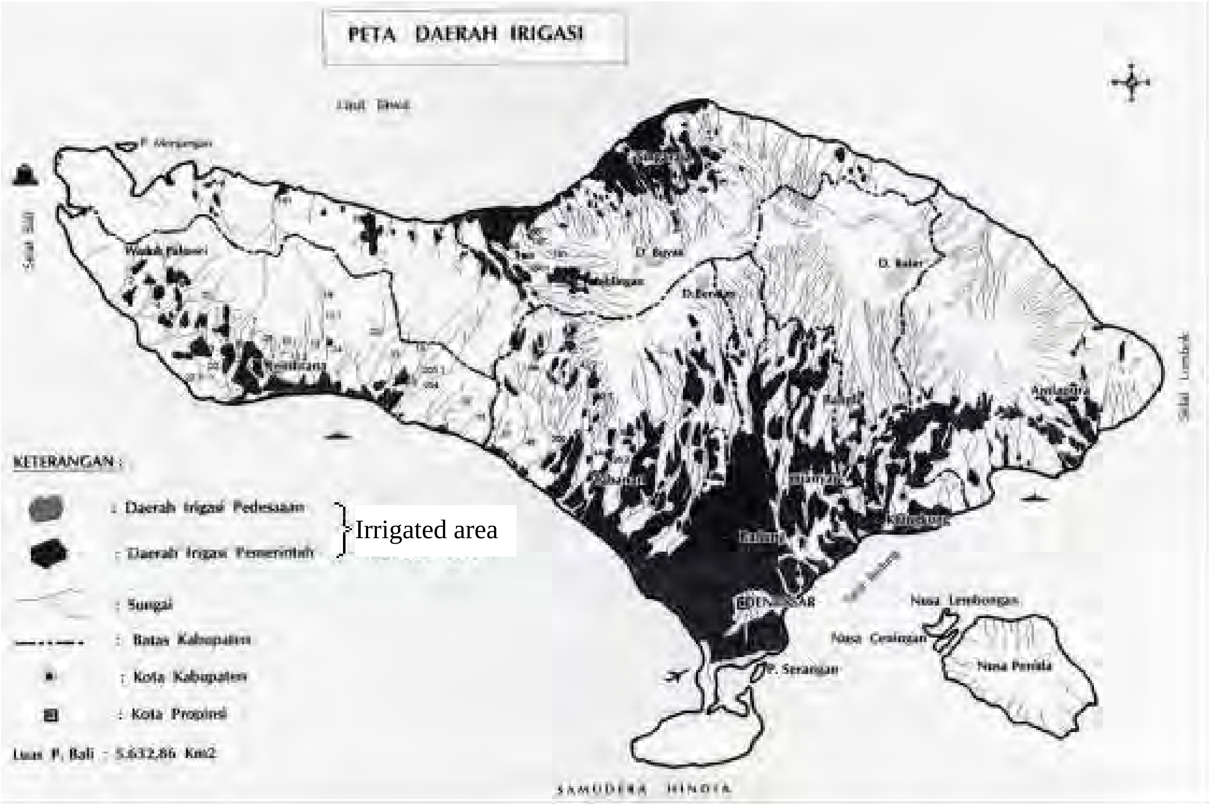
Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
1994	457	327	267	41	56	9	3	0	0	0	44	98	1,302
1995	405	257	366	279	29	12	3	0	26	53	374	349	2,153
1996	546	499	217	7	92	0	4	9	19	258	254	269	2,174
1997	577	548	69	24	8	11	13	0	1	1	39	30	1,321
1998	169	129	168	48	31	48	66	0	56	283	169	582	1,749

Source: Bali in Figures (1998)

The mountain range running from east to west, which forms the backbone of the island, includes volcanoes over 1,700 m in elevation located on the north side of the island. This topography is reflected in the formation of rivers; the rivers are long on the south side of the island and short, mostly less than 10 km, on the north side of the island. Rivers are, therefore, poorly developed on the north side of the island; many rivers that originate in water springs located at elevations of about 500 m form deep valleys, run parallel to each other and flow into the sea without forming alluvial plains.

Along the long winding rivers is an expanse of irrigated paddy fields. These paddy fields are concentrated particularly in the central south part of the island and a large part of these paddy fields are located on terraced slopes in the valley. The lifeline of paddy rice cultivation on these terraced slopes is Subak, a traditional irrigation system on Bali.

Figure 3.5.1 Water System Map of Bali Province



Source: Dinas Pekerjaan Umum Propinsi Bali (2001)
(Settlement and Regional Infrastructure Bureau, Bali Province)

The special features of Subak, which reportedly had been established in the 9th century at the latest, are listed below.

- Autonomous group with joint responsibility regarding rights, obligations and interest in paddy fields and farming.
- Elaborate technology for constructing small structures and excellent landscaping technique that can hide water facilities in a green rich environment
- The most often used structures are wells and weirs made of such materials as rocks, bamboo and wooden piles, and other materials easily available locally. Rockwork technology using volcanic rocks is particularly advanced. Waterway technology is also so advanced as to enable the construction of waterways on mountain slopes as well as long waterway tunnels and waterway bridges across valleys.
- A community comprised of paddy field owners who hold a number of shares proportionate to the area of paddy field they own. Since the community is independent from the village organization, the head of Subak and the village head are, in principle, different persons. With a waterway manager appointed to each section of the network of irrigation channels that branches out over steep and complex slopes, water is supplied to each parcel of farmland in an amount exactly proportionate to the number of shares. For this purpose, a diversion device is set up in each parcel of farmland.

- Since a number of Subak communities normally share the same river, the coordination of water use between different Subak communities is achieved through discussions at Subak Gede (the Great Subak), the alliance of Subak communities.

Water utilization and management by Subak communities help to enrich water resources on Bali. The advantages of the Subak system are described below in reference to 2.1.6 Objectives of Water Resource Development.

(1) Increasing freshwater resources by retarding the flow velocity

River water is first transported to a higher elevation not far from the river and then temporarily kept in paddy fields during which time the water partially infiltrates to the subsurface. The use of water in this way retards runoff. If the use of water is intensive in coastal regions, it will cause detrimental effects. However, on Bali, this method is used for paddy fields in middle and lower river reaches. Paddy rice cultivation in middle river reaches and the accompanying water use help to increase freshwater resources. The Subak irrigation system plays a vital role in this.

(2) Stabilization of the potential water yield

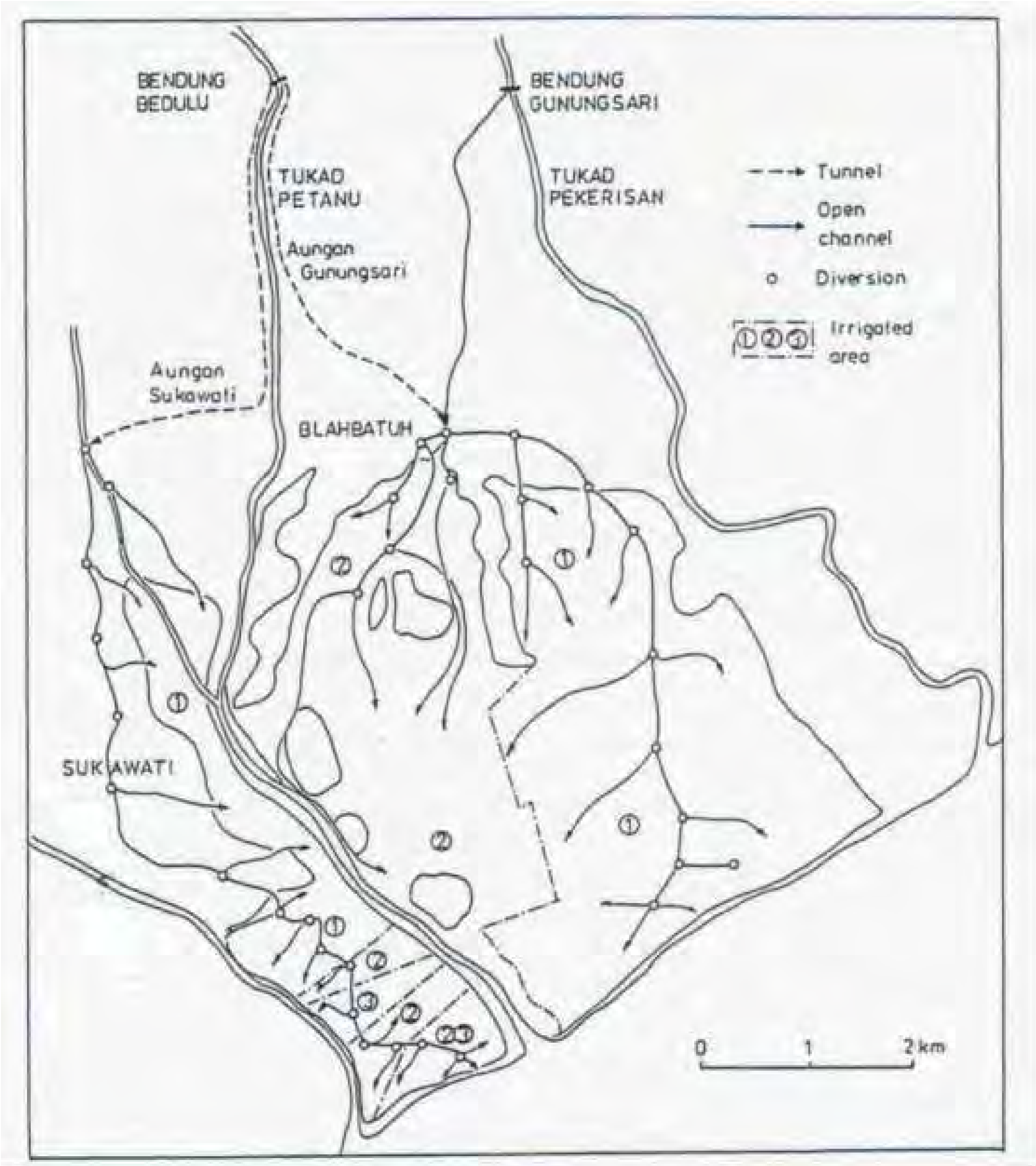
The Subak system uses multiple numbers of weirs set up along middle to lower river reaches for water intake. Despite considerable amounts of water pumped from upper weirs, sufficient amounts of water are still often available in lower river reaches, presumably because water pumped from weirs, which is first transported to paddy fields, partially infiltrates to the subsurface and returns to the river. The circulation of river water through various routes (though starting and ending in the river) will not only retard runoff but also stabilize the river discharge; water infiltration to the subsurface reduces the flood peak and creates a time lag.

Figure 3.5.2 shows an example of how the Subak system is run. This figure shows that the beneficiary area is divided into three sections to create a time lag during the paddy rice planting period. The amount of water supply to each of the three sections is adjusted during the planting period. It is clear that depending on how the system is operated, paddy rice may be harvested three times a year. Despite clear seasonal changes in the amount of rainfall, water use is stable throughout the year. This is due largely to the Subak irrigation system that helps to stabilize the river discharge.

(3) Spreading of water resources

Waterways, arranged in a network, fully demonstrate their function. As shown in Figure 3.5.1, quite a few regions find that their water demand is met. A large part of these regions are supported by the Subak system.

Figure 3.5.2 Subak System of the Pekerisan and Petanu Rivers



Source: Dinas Pekerjaan Umum Propinsi Bali

Bali is complete with a range of water management systems, the best known of which is the Subak system. By taking advantage of river water circulation (intake and return of river water) along the upper to lower reaches, the island tries to overcome its climatic disadvantages. However, regions unable to obtain sufficient supply of water still exist. Even in the central southern region relatively rich in water sources, the water use priority given to tourism has placed pressure on the use of daily-life water by residents.

The northern regions with short river lengths and low rainfalls face conditions that make the Subak system hard to run. Accordingly, small-scale irrigation development projects that mainly include the construction of dams and digging of wells are sporadically carried out, for example, under bilateral assistance programs.

The government of Bali Province has set up a goal of achieving central management of water resources, not for the purpose of increasing control and supervision, but for the purpose of increasing and standardizing the productivity of the island. For example, in the area of agriculture, the provincial government encourages paddy rice farming in water-blessed regions where the Subak system is in place and encourages dry-field farming in other regions. Through these efforts, the provincial government is attempting to solve the problem of regional disparities.

The conflict over water use between tourism and agriculture/everyday life still exists. Diversifying the forms of tourism and taking greater advantage of natural resources are considered effective solutions to this problem. This will promote the decentralization of tourist centers. Once a system is in place to allow the well-balanced supply of agricultural products to more spread-out tourist centers, it will lead to increased benefits to the entire island.

3.5.2 Selection of Suitable Sites for Subsurface dam Development

Survey targets, which are located on islands in the eastern part of Indonesia, include Bali Province, East and West Nusa Tenggara Provinces and East Timor Province (current East Timor). These target regions are largely classified into two: volcanic islands such as Bali and Lombok, and islands close to the Australian continent such as Sumba and Timor.

As explained in 3.4 Flow of Surveys for the Selection of Suitable Sites, it is preferable to narrow the candidate regions based on the procedures shown in Hydrological and Geological Surveys and in Priority of Examination. However, time restrictions necessitated the use of the following procedures for surveys. These procedures are shown below, together with the survey results.

(1) Interviews about development needs

Applications were received from four target provinces, each of which presented a list of suitable districts for groundwater development. In response to the requirements below, a total of 84 districts were recommended as suitable sites.

- Regions with no irrigation facilities
- Regions with no plans or schemes for irrigation development projects
- Regions where surface water development such as the construction of reservoirs is difficult

Table 3.5.2 Number of Districts Recommended for Surveys

Name of the Province	Number of Recommended Districts
Bali Province	
Bali	7
West Nusa Tenggara Province	
Lombok	9
Sumbawa	8
East Nusa Tenggara Province	
Sumba	12
Flores	15
West Timor and other islands	24
East Timor	9

(2) Hydrological and geological surveys

From among the 84 districts above, 25 districts with clear geographical characteristics of suitable sites for subsurface dam development were selected (see 3.3.1) based on existing topographic and geological maps.

(3) Site reconnaissance and electric prospecting

The propriety of the selected 25 districts was assessed through site reconnaissance. The items for assessment are shown in Table 3.5.3. The assessment criteria were set as below. The districts with conditions that make it difficult to estimate the depth of the hydraulic basement were assessed using electric prospecting (Table 3.5.4).

(1) Necessity

- a: Large annual fluctuations in the groundwater level
- b: Despite large fluctuations in the groundwater level, the presence of a thick aquifer may allow water intake from a deep well
- c: Absence of large fluctuations in the groundwater level

(2) Functionality

- a: (In terms of porosity) The widespread distribution of high-quality aquifers may enable a reservoir capacity exceeding 100,000 m^3
- b: Despite the widespread distribution of high-quality aquifers, they are not likely to enable a reservoir capacity exceeding 100,000 m^3
- c: The bottom layer of the aquifer is not likely to function as a hydraulic basement

(3) Efficiency

- a: Dam sectional area of 10,000 m^2 or less and dam height of 30 m or less
- b: Dam sectional area of 10,000 m^2 or more and dam height of 30 m or less
- c: Dam sectional area of 50,000 m^2 or more and dam height of 30 m or more

General assessment

- A: “a” for all assessment items
- B: “a” or “b” for each assessment item
- C: “c” for any one of the assessment items

(4) Assessment

Although no district was ranked A in the general assessment, six districts were ranked B. These six districts are therefore assessed here as suitable sites worthy of consideration for subsurface dam development (suitable sites for subsurface dam development). Incidentally, the six districts ranked B in the general assessment can be further classified into two types based on geographical conditions; five districts are classified as the “top of the alluvial fan” type and the one remaining district is classified as the “karst” type.

For many of the districts ranked C in the general assessment, groundwater development that uses methods other than subsurface dam development is considered a more realistic approach. It would be effective to consider, for example, deep groundwater development and the infiltration of surface water to the subsurface.

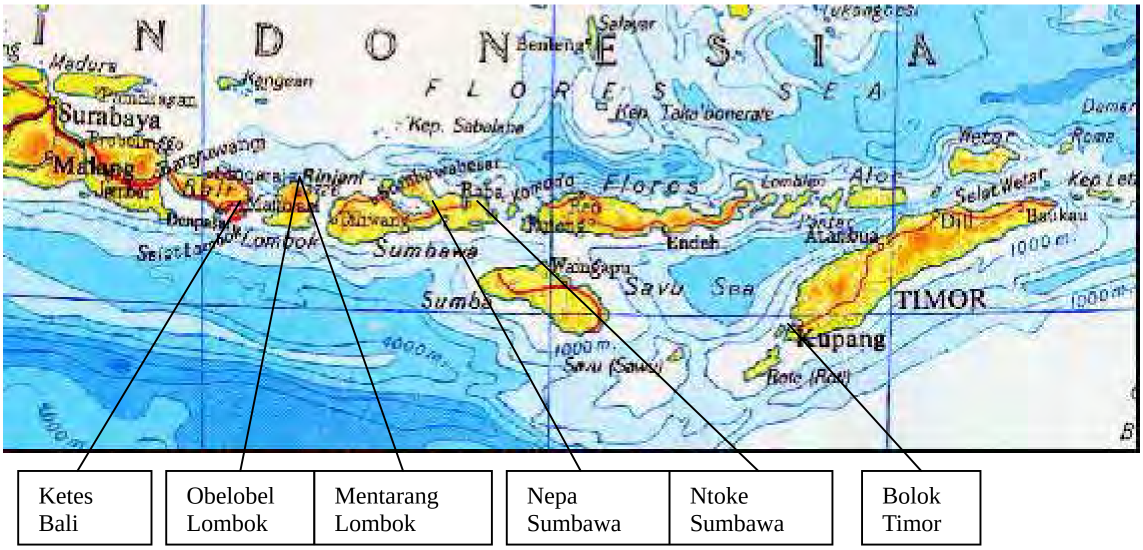
Table 3.5.3 Assessment of Candidate Sites for Subsurface dam Development

Island Name	Site	Necessity (Water level fluctuations)	Functionality (Aquifer capacity)	Efficiency (Cross section)	General Assessment
Bali	Tengal	c	b	c	C
	Seraja	c	b	b	C
	Tudalitem	b	a	c	C
	Ketes	a	a	b	B
	Tejakula	c	b	b	C
Lombok	Akarakar	b	a	c	C
	Batugembung	b	a	c	C
	Lendang	b	b	c	C
	Beburung	a	a	c	C
	Obelobel	a	a	b	B
	Mentarang	b	a	b	B
	Pedamekan	b	a	c	C
	Belanting	b	a	c	C
	Kuntbian	a	a	c	C
Sumbawa	Teluk	b	c	c	C
	Nepa	b	b	a	B
	Ntoke	b	a	a	B
	Sancara	c	b	b	C
	Tolotangga	c	c	c	C
	Tente	c	b	c	C
	Piong	c	b	c	C
Timor	Noelnunfisa	b	b	c	C
	Noelletometo	c	c	c	C
	Sikumana	b	a	c	C
	Bolok	b	a	a	B

Table 3.5.4 List of Dimensions of Candidate Sites for Subsurface dam Development

Island	Region	Electric Prospecting Number of Measured Points	Estimated Cross Sectional Area	Aquifer Geology	Basement Geology	General Assessment
Bali	Ketes	60	350m*30m	Alluvial gravel layer	Volcanic breccia	B
Lombok	Beburung	50	700m*100m	Alluvial gravel layer	Volcanic rock	C
Lombok	Obelobel	50	400m*60m	Alluvial gravel layer	Volcanic breccia	B
Lombok	Mentarang		750m*50m	Alluvial gravel layer	Volcanic breccia	B
Lombok	Pedamekan	50	500m*70m	Alluvial gravel layer	Volcanic breccia	C
Sumbawa	Nepa	12	400m*20m	Alluvial gravel layer	Volcanic breccia	B
Sumbawa	Ntoke	12	200m*20m	Alluvial gravel layer	Volcanic breccia	B
Timor	Sikumana	52	5,000m*20m	Limestone	Pre-Tertiary Period sedimentary rocks	C
Timor	Bolok		10m*10m	Limestone	Volcanic breccia	B

Figure 3.5.3 Location Map of Candidate Sites for Subsurface dam Development



3.6 Examples of Surveys in Mexico

The northwestern part of Mexico has a low annual rainfall of 100 to 200 mm and has a far greater potential evapotranspiration, which makes it difficult to conserve water resources. These background factors have exacerbated problems such as salt accumulation in irrigated farmland, a resultant increase in abandoned farmland, and the salinization of groundwater as a result of excessive groundwater pumping in coastal regions.

The present state of the salt damage was, therefore, determined in order to consider what kinds of measures could be taken to solve the problem. At the same time, the possibility of developing a subsurface dam was examined as one of the possible options.

3.6.1 Current State of Salt Damage and Water-conserving Irrigation

(1) Factors causing salt damage

Salt accumulation refers to a phenomenon of continuous buildup of water-soluble chlorides on the ground surface as a result of increases in the groundwater level and capillary increases. This phenomenon is caused by poor drainage. Irrigation with high-salinity water will accelerate salt accumulation. Poor drainage specifically means poor runoff of water. The two factors below are presumed to be causing this problem:

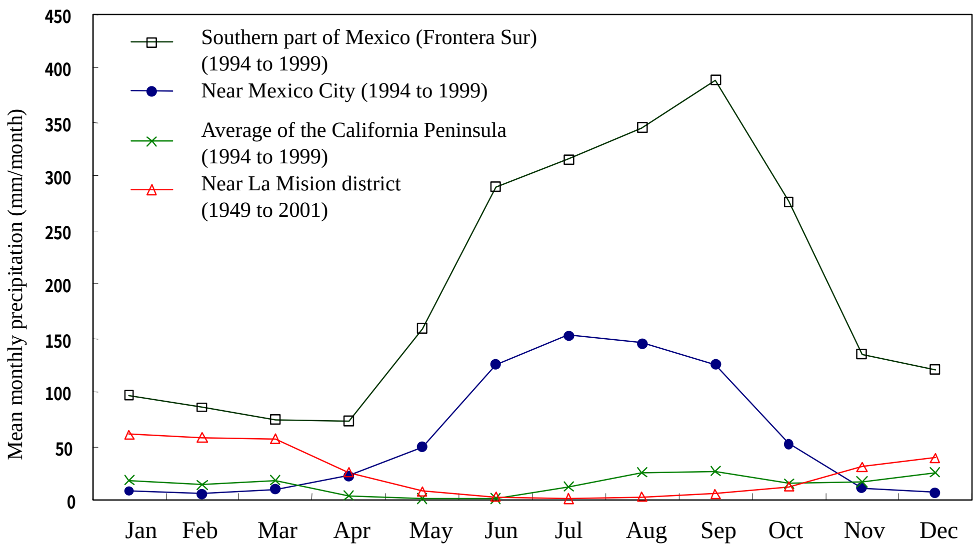
- Absence of a hydraulic gradient
- Absence of irrigation water in amounts greater than the amounts lost from evaporation

(2) Current meteorological and hydrological state

Although Mexico as a whole has a mean annual precipitation of 772 mm (1941 to 1999 statistics), its northwestern part with a low precipitation rate is made up of dry and semi-arid regions. Figure 3.6.1 shows the distribution of mean annual precipitation in Mexico and Figure 3.6.2 shows the mean monthly rainfalls at representative points. The district of La Mision (the site survey district; to be explained later) in the northern part of the California Peninsula has virtually no rainfall in summer.

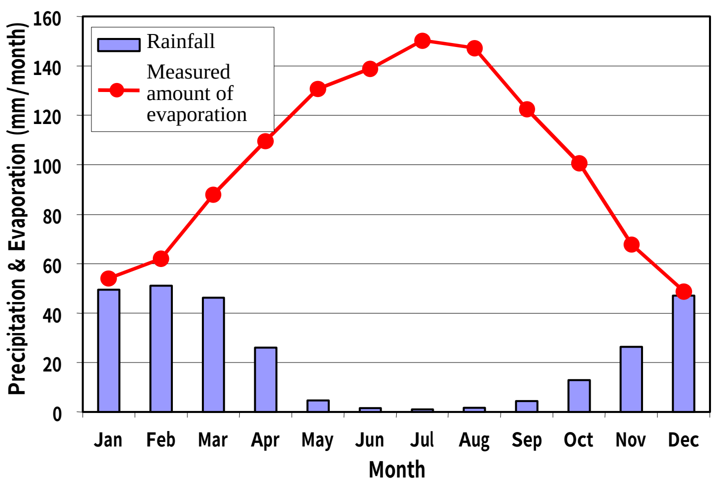
Figure 3.6.1 Mean Annual Precipitation in Mexico

Figure 3.6.2 Mean Monthly Precipitations in Various Locations in Mexico



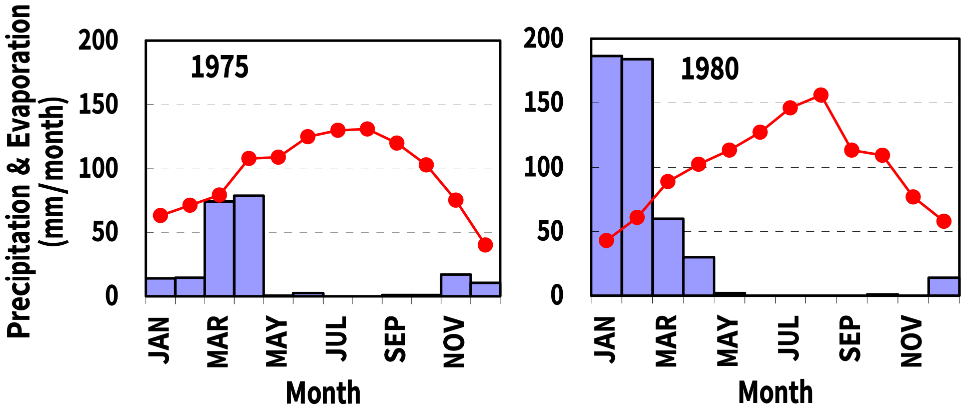
In the northwestern part with a low rainfall, the potential evapotranspiration is higher than the rainfall throughout the year. Figure 3.6.3 compares mean values of rainfall and evaporation in Ensenada, a city in the northern part of the California Peninsula.

Figure 3.6.3 Mean Monthly Precipitation (1923 to 1989) and Mean Monthly Evaporation (1949 to 1989) in Ensenada



A look at the data on a yearly basis shows that while the evaporation has remained at the level of about 1,200 mm/year with little fluctuation, the precipitation has fluctuated widely, sometimes even exceeding evaporation. Similarly, a look at the balance between rainfall and evaporation in 1975 and 1980 in Ensenada (Figure 3.6.4) shows that although evaporation exceeded rainfall throughout the year in 1975, rainfall exceeded evaporation in January and February in 1980, producing a total water surplus of 266 mm in the two months. This surplus can induce runoff and resultant removal of salt damage. On the other hand, regions where rainfall never exceeds evaporation are potentially susceptible to the occurrence of salt damage.

Figure 3.6.4 Rainfall and Evaporation in 1975 and 1980 in Ensenada



Regions with a low precipitation rate have no choice but to use groundwater as the water source. However, small amounts of groundwater recharge make it difficult to ensure adequate supply of water. Quite a few regions are, therefore, pumping groundwater in amounts greater than the amounts of groundwater recharge. Figure 3.6.5 shows the distribution of districts engaged in the practice of excessive groundwater pumping, in reference to the groundwater balance for each small catchment area. These districts often suffer from groundwater problems such as the lowering of the groundwater level and the infiltration of salt water to aquifers. Pumping and irrigating salinized groundwater may pose the danger of accelerating salt damage.

Figure 3.6.5 Districts Engaged in the Practice of Excessive Groundwater Pumping in Mexico

(3) Present state of salt damage

In Hermosillo, an irrigated coastal district in Sonora State in the northern part of Mexico (located at an elevation of approximately 60 m with a cultivated land area of 51,000 ha), the groundwater level, which was 25 m below the earth surface in 1970, was found to have dropped to 50 m below the earth surface 30 years later. The pumping of groundwater from deeper layers had also increased the occurrence of the infiltration of high-salinity water. The irrigation of salinized water had caused salt damage that led to an increase in abandoned farmland. Farmers had repeatedly abandoned farmland when the salinity in the soil exceeded 1,000 ppm and replaced it with other undeveloped farmland.

These circumstances forced agricultural producers to come under strict total volume control regarding water intake. In 1977, concerned parties set up a steering committee, which passed a decision to cut by half the amount of water intake in stages during a 13-year period up to 1990. This decision, as a result, increased the application of water-conserving farming methods such as drip irrigation. As of 2000, the area of farmland under water-conserving irrigation totals 12,300 ha.

(4) Basic principles for salt damage reduction measures

In consideration of weather conditions described above, the basic principles for salt damage reduction measures are discussed below.

- To create an environment that causes runoff (drainage)
- To reduce the amount of irrigation water to a required minimum
- To prevent evaporation
- To introduce salt-resistant trees and crops

(5) Development and conservation of groundwater

Measures carried out are summarized below.

a) Basic measures concerning groundwater problems

- Saving of the amount of water intake through improved irrigation efficiency (water-conserving irrigation)
- Prevention of evaporation using vinyl sheets to cover cultivated land (mulching)
- Introduction of water intake regulation by public agencies
- Voluntary management of each groundwater utilization district by users
- Prevention of water quality degradation
- Availability of replacing water sources (use of treated water and desalination of seawater)

b) Precautions when carrying out measures

- Regions with large seasonal and yearly fluctuations in the rainfall and with clear division between the flood and drought seasons may experience wasted runoff water during the flood season. Although one possible measure to store and effectively use wasted runoff water is the construction of an surface dam, this means a large water loss from evaporation and it is difficult to locate sites that satisfy the topographic and geological requirements to ensure sufficient storage.
- When using groundwater, the pumping yield must be limited to a level at which the groundwater flow can be maintained. It is important to promote the use of shallow groundwater, a circulating water resource that can be recovered relatively easily by the recharge of rainfall and other precipitation. It is necessary at the same time to use great care not to cause the lowering of the groundwater level over time.

- Once an aquifer is contaminated, it is often the case that the recovery takes a long time or that the recovery is virtually impossible. It is therefore necessary to ensure thoroughness when cleaning drainage facilities.

- It is important to perform proper intake control, for example, by monitoring, if necessary, the trends in groundwater volume and quality to detect early signs of groundwater problems and take required measures. It is preferable that groundwater users take the lead in intake control such as monitoring and introduction of voluntary regulations.
- To effectively use limited resources, it may be necessary at times to conserve water and reduce pumped discharge, for example, by improving the water-conserving irrigation technology, increasing the efficiency of intake and water utilization facilities and improving intake methods.
- Measures such as the construction of a subsurface dam and the promotion of subsurface infiltration of surface water may prove effective in increasing groundwater recharge.

c) Specific measures

Mexico's Comisión Nacional del Agua (CNA) (or National Commission of Water) is an administrative body with legal powers over the development, supply and management of water resources. As part of its powers, the commission is promoting various measures, for example, measures to reduce the pumped discharge of groundwater, improve water conservation and utilization efficiency and develop substitute water sources such as treated water.

The National Water Law established in 1992 has stipulations regarding groundwater as follows:

- Since groundwater is a national property, the use of groundwater requires CNA permission. CNA permission is granted in the presence of a sufficient amount of groundwater and with priority given to drinking purposes.
- It is obligatory to set up a meter in the well and cooperate in the groundwater survey undertaken by the CNA (this requires stopping the pump at least 24 hours before simultaneous observation of groundwater levels).
- The CNA apportions annual quotas for water yield and imposes tax on water used for drinking and industrial purposes on an as-used basis. However, no tax is imposed on water used for agricultural purposes.
- The right to use groundwater can be registered and resold to a third party, if permitted by the CNA.

Apart from the efforts mentioned above, the CNA is encouraging groundwater users themselves to perform proper groundwater management in each groundwater utilization zone and is also promoting the establishment of groundwater technology councils comprising groundwater users throughout the country. Through technical lectures and other similar events at these councils, the CNA is helping groundwater users to learn the correct knowledge about groundwater and learn about groundwater problems caused by excessive pumping. Moreover, a system is in place making it mandatory for groundwater users themselves to observe groundwater levels and at the same time to provide information such as pumping methods and water yield to the CNA. As of 1999, councils have been founded in eight water utilization zones.

(6) Reuse of drainage

Specific examples of measures undertaken are presented below.

- In the Santo Domingo district in Baja California Sur State, daily-life drainage is led to a lake cut off from the open sea. When the sludge is settled, the top water is used for irrigating pasture.
- Instituto Mexicano de Tecnología del Agua (IMTA) (or the Mexican Institute of Water Technology) carried out tests on the use of treated sewer water and other recycled water for irrigation purposes under a research collaboration project for effective utilization of agricultural water sources (1998 to 2001).

(7) Purification and seawater desalination

Specific examples of measures undertaken are presented below.

- Farmers who own farmland of approximately 3,000 ha in Erumosillo irrigated district and conduct farming have a farm pond of 120 m × 120 m × 5 m (water depth) installed to store and effectively use pumped groundwater. Fish are placed in the pond to prevent algae proliferation.
- In coastal regions in Baja California State, some of the farmers are desalinating saltwater, although on a small scale, and using desalinized water for irrigation.

(8) Water-conserving irrigation

Specific examples of measures undertaken are presented below.

- In the Santo Domingo district in Baja California Sur State, for the purposes of preventing the lowering of the groundwater level and increasing farmland that can be irrigated, water-conserving agriculture was introduced, which, for example, uses relocatable pipelines, drip irrigation and irrigation of liquid manure. The end result is successful cultivation of high-quality fruits and vegetable.

Transported water through a relocatable pipeline, performed leaching, infiltrated water to the subsurface and drained water through underdrains.

Embedded pipelines of the water supply system as part of water conservation efforts to prevent evaporation and improve irrigation efficiency

(9) Forced leaching of salts

Specific examples of measures undertaken are presented below.

- The Texcco Lake greening project in the northeastern part of Mexico City was aimed at greening a salt-damaged area as large as 9,000 ha. After digging drainage channels, performing leaching and doing other preparatory work, native salt-resistant gramineous grasses and trees were planted.
- Leaching was performed on salt-damaged irrigated farmland in the southern part of Guanajuato State.
- On salt-damaged irrigated farmland in Sonora State, the survey of the distribution of salt-damaged areas was carried out using the remote sensing method. Based on the survey results, a number of measures were taken including the relocation of water source wells, renovation of irrigation facilities, leaching, charging of chemical material and installation of drainage channels.

(10) Introduction of salt-resistant trees and crops

- In La Paz district in Baja California Sur State, as part of a partner project by the Japan International Cooperation Agency (JICA), a local agricultural research institute is conducting joint tests with a Japanese university (Tottori University) for the purpose of introducing drought- and salt-resistant crops or high-yield crops. For example, the following crops are being tested for introduction: opuntia, the berries and leaves of which can be used for edible purposes and the insects living on the leaves can be used to produce dye; salt-resistant beans (Phaseolus and Vigna), and Salicornia, a salt plant, the berries and leaves of which can be used as food and feed. Cultivation methods that can economize on irrigation water and manure are also introduced on a trial basis.

3.6.2 Selection of Suitable Sites for Subsurface dam Development

Baja California State located in the northwestern end of Mexico was selected as the survey target. The available water resources in Baja California State are estimated to be 3.381 billion m^3/year, which is broken down into 2.19265 billion m^3/year of surface water and 1.18835 billion m^3/year of groundwater. Of the available surface water, 1.85 billion m^3/year comes from the Colorado River, meaning that the water from the river accounts for more than half of the available water in the state. However, the water from the river only benefits the plain area in the inner part of the California Bay, and other areas are quite heavily dependent on groundwater.

With regard to groundwater level fluctuations, the year-by-year reduction of the groundwater level rather than seasonal fluctuations is considered to be a more serious problem. This circumstance makes it important to take measures to reduce the salinization of groundwater. Since the target region is hit by a hurricane every eight to nine years, the heavy rain brought by the hurricane provides a precious water source. One of the potentially promising measures to store and effectively use the rainwater is the construction of a saltwater infiltration prevention dam.

As explained earlier in 3.3.1 Geographical Characteristics, the sites suitable for the construction of a saltwater infiltration prevention type subsurface dam are drowned valleys or coastal karsts. With this in mind, suitable sites for subsurface dam development were selected. To allow adequate flexibility for the water balance susceptible to wide year-to-year fluctuations, for example, caused by the occurrence of a hurricane every eight to nine years, the site requirements were set as follows: a reservoir capacity of several millions of m^3 or greater.

(1) Geological analysis

Drowned valleys can be easily found on a topographic map. What is considered to be an issue is the water permeability of the soil of the subsurface valley. To understand the trends in soil properties, a wide-area geological map was analyzed.

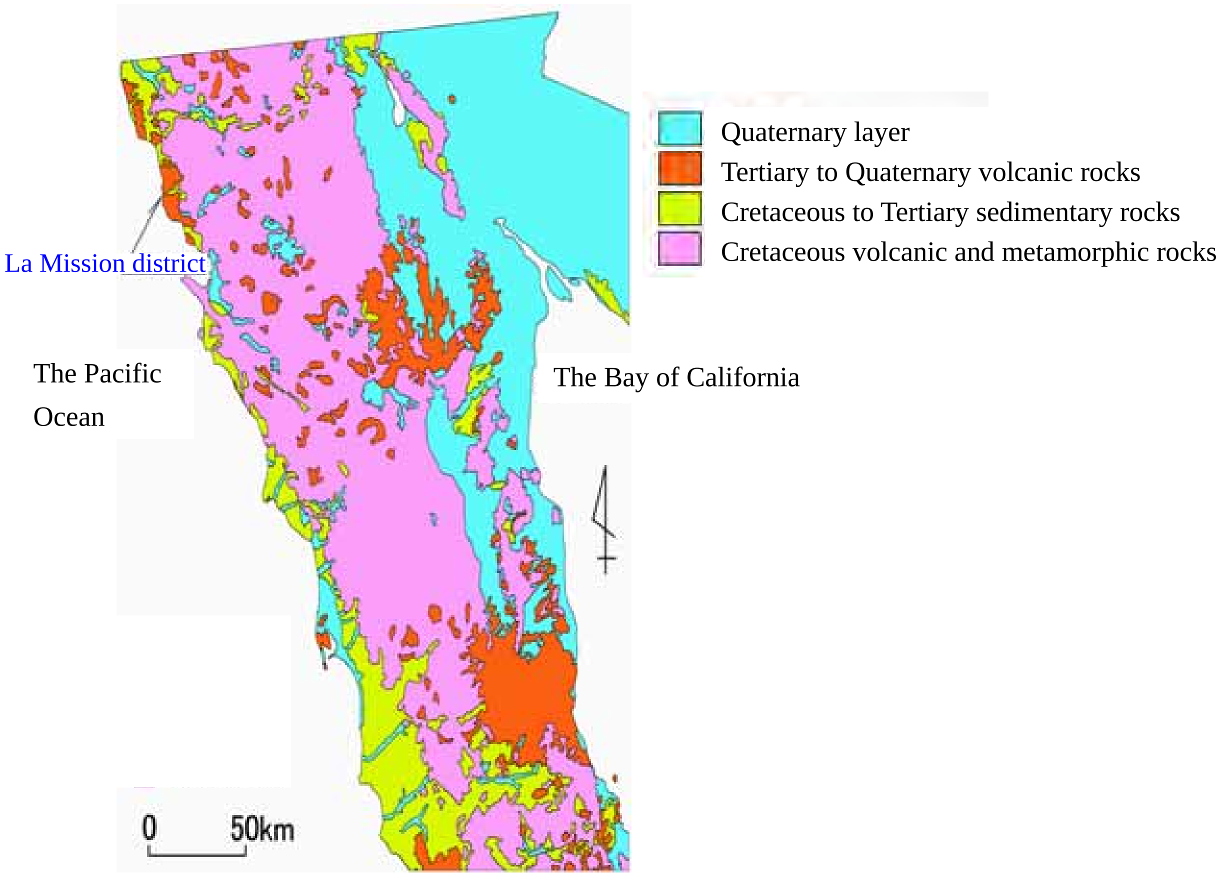
Baja California State is geologically characterized, as shown in the geological map in Figure 3.6.6, by the basement primarily composed of metamorphic rocks and Cretaceous Period igneous rocks, which is covered by sedimentary and volcanic rocks from after the Cretaceous Period. Limestone, an indicator of a potentially productive aquifer for a subsurface dam, can possibly be found in sedimentary rocks from after the Cretaceous Period. The limestone, if distributed in relatively high concentration, forms a karst topography. Another advantageous geographical feature is the presence of a drowned valley, where Quaternary strata are found.

(2) Catchment water balance

The National Commission of Water (CNA), as part of its water resource management, divided the national land area into small catchment areas and designated the main area with aquifers in each small catchment area as a unit of the groundwater utilization zone. Based on this, the CNA established a system to supervise the general water balance in each groundwater utilization zone. Baja California State, as shown in Figure 3.6.7, was divided into 48 districts for the purpose of water balance management.

According to the CNA estimates, districts engaged in the practice of excessive pumping, where the water yield was greater than the amount of recharge, were nine in number in Baja California State (Table 3.6.1). The coastal regions in these districts are highly likely to be exposed to saltwater infiltration to groundwater. Another 18 districts were found in equilibrium in terms of the balance between the amount of recharge and the water yield. The amount of groundwater recharge exceeded the water yield in only 21 districts.

Figure 3.6.6 General Geological Map of Baja California State



(3) Propriety assessment

Based on the analysis of the general water balance, a total of three districts were selected as suitable sites for development from among districts with the tendency toward excessive pumping. The selection criterion was that the district must have geographical features such as the presence of a drowned valley in the estuary.

Complementary site reconnaissance was performed in these three districts to examine site conditions. All these districts including their surrounding areas have high potential for agricultural development. The entire farmland area in Baja California State is in excess of 300,000 ha, of which approximately 200,000 ha of land is irrigated. Among the main agricultural products of these regions are wheat, green tomatoes, grapes and strawberries. Intensive agricultural production through the introduction of irrigation has successfully increased the unit yield of various crops including green tomatoes, wheat, barley, corn, sorghum and potatoes.

Figure 3.6.7   Groundwater Utilization Zone Units in Baja California State

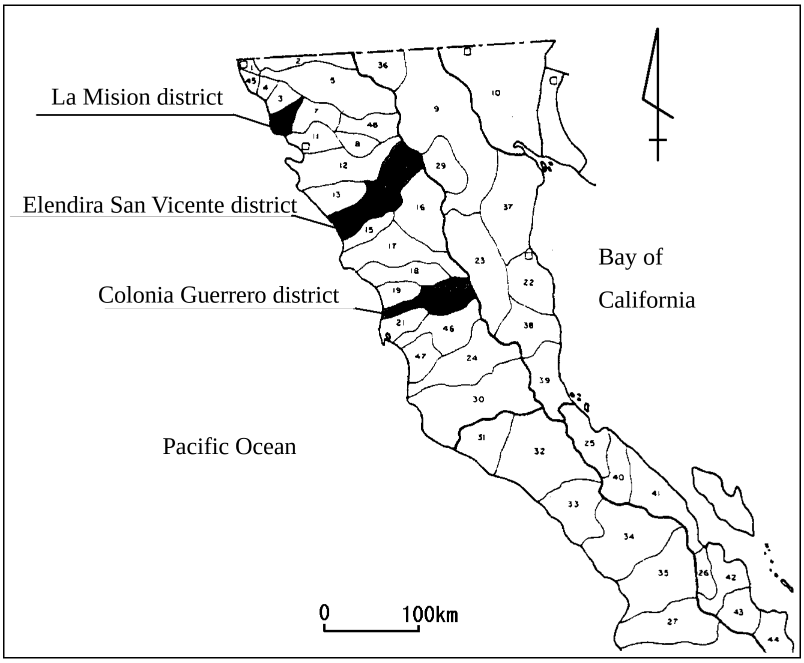


Table 3.6.1   General Water Balance in Groundwater Utilization Zones in Baja California State

Aquifer Name	Groundwater Recharge (1 million m^3/year)	Water Intake (1 million m^3/year)	Groundwater Balance (1 million m^3/year)	Aquifer Name	Groundwater Recharge (1 million m^3/year)	Water Intake (1 million m^3/year)	Groundwater Balance (1 million m^3/year)
Ojos Negros	19.50	25.50	-6.00	Calamajue	2.00	0.06	1.94
Valles de Mexicali	700.00	735.00	-35.00	Agua Amarga	1.00	0.02	0.98
Maneadero	20.80	25.70	-4.90	La Bocana - Llanos San Pedro - Las Palmas	1.50	0.01	1.49
La Trinidad	23.00	30.00	-7.00	San Rafael - La Palma	1.00	0.01	0.99
Camalu	2.75	4.00	-1.25	El Progreso - El Barril	1.00	0.01	0.99
Col. Vicente Guerrero	19.52	21.42	-1.90	El Socorro	1.30	0.77	0.53
San Quintin	19.10	24.40	-5.30	Tijuana	17.80	17.80	0.00
San Simon	13.50	19.00	-5.50	Tecate	6.00	6.00	0.00
Real del Castillo	6.00	9.00	-3.00	El Descanso	0.40	0.35	0.05
Laguna Salada	15.35	14.00	1.35	Los Medanos	0.40	0.35	0.05
Bahia de San Luis G.	0.50	0.30	0.20	Las Palmas	6.50	6.50	0.00
Bahia de Los Angeles	0.50	0.11	0.39	La Mision	7.00	6.80	0.20
Villa Jesus Maria	1.50	0.78	0.72	Guadalupe	18.00	18.00	0.00
Llanos del Berrendo	2.00	0.11	1.89	Ensenada	3.50	3.60	-0.10
Jamau	2.50	0.01	2.49	Santo Tomas	7.10	7.00	0.10
San Fernando - San Agustin	3.50	1.04	2.46	San Vicente	8.00	7.50	0.50
Santa Catarina	1.50	0.01	1.49	Canon de La Caletura	3.50	3.50	0.00
Punta Canoas - San Jose	1.03	0.02	1.01	San Rafael	7.00	7.00	0.00
Lag. Chapala - Las Palomas	1.00	0.02	0.98	San Telmo	6.00	6.00	0.00
La Bachata - Santa Rosaliita	1.50	0.11	1.39	San Felipe - Punta Estrella	6.00	6.00	0.00
Nuevo Rosarito	1.50	0.49	1.01	Valle Chico - San Pedro M.	12.00	12.00	0.00
El Chinero	0.50	0.25	0.25	El Rosario	3.00	3.00	0.00
Matomi - Puertecitos	0.50	0.01	0.49	La Rumorosa - Tecate	0.10	0.10	0.00
El Huerfanito	0.50	0.01	0.49	Rosarito	1.40	1.60	-0.20

3.7 Summary

The results obtained from the preliminary survey are considered in the section below.

3.7.1 Eastern Part of Indonesia

Since many regions with small catchment areas are susceptible to large differences in the potential water yield between the rainy and dry periods as well as to the underflow of river water during the dry period, the construction of a subsurface dam is expected to have a significant impact. However, even these regions have a relatively high recharge rate thanks to an annual rainfall in excess of 1,000 mm. Therefore, the construction of a subsurface dam is not the final option. A large part of these regions can satisfy their water demand by collecting and distributing river water and developing deep groundwater.

Regions with relatively large catchment areas may be able to promote the infiltration of surface water to the subsurface by developing farmland and a network of agricultural waterways in their middle reaches. The retarded runoff may moisten the land and increase the stability in groundwater use in the lower reaches.

Even if present circumstances make it premature to develop a subsurface dam, it is important to preliminarily locate suitable sites for subsurface dam development in anticipation of future increases in water demand. The districts selected from the surveys, if only viewed from the geographical perspective, have ideal conditions. However, in order to evolve subsurface dam development projects into more specific projects, it is necessary to form a consensus in the local community, prepare a clearly visioned plan for wide-area development and determine the water demand.

3.7.2 Northwestern Part of Mexico

Since the northwestern part of Mexico has a low annual rainfall of 100 to 200 mm and suffers from potential evapotranspiration far greater than the rainfall, it is essential to ensure water conservation and at the same time reduce water exposure to a minimum. The previous section explained various measures such as the reuse of drainage, desalination of seawater, construction of pipeline waterways and introduction of drip irrigation and other water-conserving farming methods. The priority issue is to increase the application of these measures.

In the absence of proper water resource management this part of Mexico would suffer not only from water shortage but also from soil degradation due to salt damage. Regions already suffering from salt damage must perform leaching – the washing out of salts from soil using a large amount of water – before resuming agricultural activities. Even in regions not suffering from salt damage at present, it is important to ensure adequate drainage in order to prevent salt damage.

To realize more systematic water supply and distribution, stable water sources are needed. One of the possible ways to achieve this is the construction of a subsurface dam. Subsurface dam development is expected to reduce large year-to-year fluctuations in the rainfall and the resulting year-to-year fluctuations in the recharge rate. Since drowned valleys in coastal regions are considered suitable for subsurface dam development from a perspective of geographical features, the construction of a subsurface dam with saltwater infiltration prevention function is considered effective.

Chapter 4 Site Survey

This chapter proposes a technique for surveying feasible subsurface dam development areas selected by a preliminary survey. Based on a survey of model areas, the "Evaluation of Subsurface Dam Construction Effects" and "Subsurface Dam Implementation Plan" are now under study.

4.1 Study Items

The site survey is targeted at feasible subsurface dam areas selected by the preliminary survey. This prepares information necessary for M/P planning. The study items should be organized by referencing "2.6.1 Flow of Water Resources Development."

(1) Water source location

Determine the subsurface dam axis by considering the reservoir capacity and the cut-off efficiency. If necessary, also propose an auxiliary water source.

(2) Facility study

Study feasible cut-off wall construction methods and clarify their limit depths for building. Design a cut-off wall to roughly determine such dimensions as the dam height and dam length. In addition to the cut-off wall, propose necessary facilities for intake and distribution, such as wells and channels. Also study the preparation level of each facility. Set the survey accuracy so that the quantity error at each facility will be within 20 to 25%.

(3) Exploitable water quantity

By assuming continuous intake at a fixed rate, calculate the exploitable water quantity per day. It is preferable to suppress an error to within 20 to 25%.

(4) Supply and distribution method

Roughly determine the possible supply range from the exploitable water quantity. Estimate the effects of water supply, especially in terms of agricultural productivity.

(5) Project expenses

Estimate expenses on the project.

(6) Environmental changes

Forecast changes of the water environment by installation of the cut-off wall and distribution to the beneficiary area.

4.2 Survey Flow

Listed below are the necessary survey items, which take into consideration the study items introduced in the previous section.

4.2.1 Topographical and geological surveys

These surveys are aimed at checking the topography of the target catchment area and the distributions and characteristics of the hydraulic basement and aquifer to determine “(1) Water source location” described in the previous section. This is also used to obtain information necessary for “hydraulic analysis” to be explained later. The necessary information is as follows:

- General topography of the catchment area
- Aquifer

  Stratigraphy, effective porosity, and hydraulic conductivity
- Hydraulic basement

  Geology, shape (contour), and hydraulic conductivity of the hydraulic basement in the aquifer distribution area

The survey items are as follows:

(1) Topographical survey

Collect topographical data, measure around the aquifer distribution area, and create a topographical map (scale: about 1:5,000).

(2) Physical prospecting

Conduct electric prospecting and seismic prospecting to estimate the shape (contour) of the hydraulic basement in the aquifer distribution area. Select an effective prospecting technique taking into consideration the geological combination of hydraulic basement and aquifer. Since survey accuracy cannot generally be expected, the prospecting range may be narrowed down with priority given to the determination of dam site.

(3) Boring survey

Conduct core boring and tests for field permeability, pumping and soil. This survey is aimed at checking the depth of hydraulic basement and the permeability of aquifer and hydraulic basement. Do not rely too much on the test results after core boring, but attach importance to core observation. It is possible to gain extensive information on hydraulic conductivity and effective porosity from empirical core observation.

4.2.2 Meteorological and hydrological surveys

These surveys are aimed at checking water circulation in the target catchment area to obtain information necessary for “hydraulic analysis” to be explained later. The survey items are as follows:

(1) Meteorological survey

Collect meteorological data from an existing station in or near the catchment area. In addition to daily rainfall data, also collect data on gage evaporation for estimating evapotranspiration, sunshine duration, temperature, and humidity data. It is preferable to collect data for the past 10 years or more. If there is no station in the catchment area, install a precipitation gage and continue observation for at least one year.

(2) Surface-water flow rate survey

Collect flow rate observation data on rivers and other surface waters. If necessary, install observation equipment and continue observation. Like the meteorological survey, it is preferable to collect data from an existing station for the past 10 years or more and from new observation equipment for the past year or more.

(3) Groundwater level observation

Check the plane distribution of the groundwater level and its fluctuation. It is necessary to understand annual fluctuation and secular fluctuation. Use boreholes for groundwater level observation. Collect data at least once from each of as many boreholes as possible. Continue observation for at least one year. If the labor force and budget are limited, reduce the number of observation holes and check the seasonal fluctuation of groundwater-level plane distribution by simultaneous observation of the groundwater level several times a year.

(4) Groundwater use survey

If groundwater is pumped into the target aquifer, collect reference materials about the pumping quantity. Data totaled by months will be sufficient. If pumping quantity measurement data is not available, estimate the pumping quantity by listening to information on use and scale (irrigation area and the number of beneficiaries) from users.

(5) Water survey

If there are any water quality problems such as salinization, it is necessary to check the water quality distribution. Measuring the electric conductivity of groundwater is an easy method of checking the water quality. If boreholes are used, not only the plane distribution but also the vertical fluctuation can be understood. If necessary, analyze the components of a sample for reference.

4.2.3 Hydraulic analysis

This analysis is aimed at digitally expressing and quantifying the law of water circulation in the catchment area using information obtained by “Topographical and geological surveys” and “Meteorological and hydrological surveys.” Based on this quantified analytical model, forecast the future of water circulation, such as the influences of subsurface dam construction. This will allow the presentation of “(3) Exploitable water quantity” and “(6) Environmental changes” explained in the previous section.

(1) Basic policy

This survey is aimed at analyzing the flow rate that cannot be measured directly and the tendency of its fluctuation with the passage of time. The analytical model will basically have a structure where the quantity of water charge to the ground of the catchment area and that of water intake from there are input and the "flow rate" and "groundwater level" are output. The calculated values output here should not differ greatly from the observed values obtained by "Meteorological and hydrological surveys."

A simpler analytical model is better for longer and broader analysis. In addition, calculation time and survey expense can be saved. The transition of "flow rate" with the passage of time is a key in project planning. To simplify the model, priority should be given not to the proximity of calculated values and observed values but to the similarity of their change rates in verification.

Through verification, the accuracy, frequency, and quantity of data necessary for "Topographical and geological surveys" and "Hydrological and meteorological observation surveys" can also be considered. For some items, the data quantity and preciseness may hardly affect the analytical accuracy. For other items (or places), the data quantity or fitness may be decisively lacking.

The analytical model is simplified by analysis at two stages. "Water balance analysis" is conducted to roughly check the water circulation in the catchment area and "Groundwater flow analysis" is focused on water flow in the aquifer distribution area.

(2) Water balance analysis

Create a numeric model (series tank model) to roughly reproduce the water circulation. Using this model, calculate the water inflow into the subsurface dam reservoir area and the water runoff from there in time series. The rough flow is as follows:

1) Divide the catchment area into several sub-catchment areas (blocks). For each block, set "Vertical permeation tank" representing permeation from the surface to subsurface and "Lateral flow tank" representing groundwater flow.
2) Using the results of "Topographical and geological surveys", set analytical parameters and construct a basic structure of equations.
3) According to the equations, enter rainfall and intake data and calculate the inflow and runoff in each block (also the groundwater level for the aquifer distribution area) by time series.

Table 4.2.1Outline of Series Tank Models

	Vertical Permeation Tank	Lateral Flow Tank
Model description	Downward permeation from the surface to underground	Formation of the groundwater surface by permeation from the surface Lateral flow of the groundwater (connection with another block)
Basic equation of flow	V = c*S*H V: Permeation quantity c: Permeation constant (runoff rate) S: Storage rate H: Tank storage amount	Q = K_0*S*(Hu−Hd)/L Q: Lateral flow rate of the groundwater K_0: Saturated hydraulic conductivity of the aquifer S: Mean permeating sectional area Hu−Hd: Water level difference between the upstream and downstream tanks L: Inter-tank distance
Model parameters	Surface runoff, evapotranspiration, hydraulic conductivity, and thickness of the soil and unsaturated zone	Hydraulic conductivity, basement form, and storage rate (effective porosity)
Input	Precipitation	Quantity of groundwater added from the vertical permeation tank of the surface
Output	Quantity of groundwater added to the groundwater surface	Groundwater level, groundwater flow rate, and groundwater storage

4) Compare the above-calculated values with the observed flow rates and groundwater levels.
5) Adjust the parameters (of low accuracy) related to evapotranspiration and aquifer and calculate the values again until the calculated values become close to the observed ones.

(3) Groundwater flow analysis

Create a numeric model (three-dimensional difference model) to reproduce the groundwater level plane distribution and its fluctuation in the aquifer distribution area including the assumed subsurface dam site. If the area has a problem of salinization, add a function to the model for expressing the fluctuation of salinity concentration. The outline flow is as follows:

1) Divide the plane of the target area into square grids of an appropriate size. Each grid consists of several layers of different permeability.
2) Based on the results of topographical and geological surveys, digitize the topography and the altitude of the aquifer base and construct a basic structure of equations. For the analytical parameters, adopt numeric values that do not conflict with the parameters used for the series tank model.
3) With the inflow rate (into the aquifer distribution area) calculated using the series tank model as input data, calculate the groundwater level of each grid. If the area has a problem of salinization, calculate the salinity concentration.
4) Compare the calculated values with the observed values.
5) Adjust the parameters related to aquifer and calculate the values again until the calculated values become close to the observed ones.

(4) Forecast calculation

Using the above groundwater flow model (three-dimensional difference model), forecast changes of the water environment resulting from construction of the subsurface dam.

1) Set the hydraulic conductivity to a small value where the cut-off wall is to be installed and calculate the values again. If necessary, set several patterns for hydraulic conductivity and retry the calculations.
2) By assuming the intake of a fixed quantity in the subsurface dam reservoir area, calculate the possible quantity of water intake.

(5) Study of subsurface dam operation plan

Study an operation plan to maximize the effects of subsurface dam construction. More specifically, this is to minimize dead runoff. Study the following items:

1) Adjustment of charge to the subsurface dam reservoir area
2) Annual plan of groundwater pumping
3) Intake location and quantity (m^3/day/place)

4.2.4 Feasibility examination of subsurface dam construction

By thoroughly considering the cut-off wall, intake facilities, and distribution facilities from the viewpoints of “Facility construction technology” and “Exploitable water quantity,” study an actual facilities construction plan and a water use plan to clarify “(2) Facility study,” “(4) Supply and distribution method,” and “(5) Project expenses” explained in the previous section. The cut-off wall construction technology should be checked at “Preliminary survey” because the limit depth of construction should also be made clear.

(1) Construction technology survey

Check the “Facility construction technology” for the cut-off wall, intake facilities, and distribution facilities. Study the following points:

- Limit depth of construction for the cut-off wall and intake facilities
- Limit of distribution destination (positional relationships, such as altitude difference)
- Feasibility of facility operation and management by beneficiaries

(2) Study of farm village improvement plan

By considering “Exploitable water quantity,” clarify the possible range of distribution. Study the land use and planting plans in the assumed range. For practical and lasting plans, do the following:

1) Farm fact-finding survey

   Check the number of farm households, scale, planting system, and income.
2) Land use survey

   Create maps of planting areas by produce type and land uses by seasons.
3) Water use survey

   Check the rate of water consumption from each water source by uses and seasons.

4) Request survey

Check the intentions of farmers by distributing questionnaires.

5) Basic planning of farm village development

Create a basic plan by considering the following:

- Maintaining and managing the irrigation facilities

  For efficient and democratic operation, maintenance, and management of irrigation facilities, plan the establishment of a water management union. If a similar organization already exists, reform it according to the distribution plan.

- Maintaining the ground power and stabilizing crops

  For practical planning in terms of maintaining nutrition circulation and ground power, study relations where agriculture, stock farming (using the power and dung of livestock), agro-forestry, and fishery can link up and compensate for each other.

- Reviewing the farmer support system

  While considering measures for maintaining the ground power, introduce as many kinds of produce as possible, including ones for cash, to improve the efficiency of land use. Establish an agricultural production union to support these efforts by farmers and promote local unification.

- Reviewing the distribution and sales system

  Conduct studies to promote the processing of agricultural produce and to develop a produce collection and shipping system. It is preferable that the markets and centers of consumption are close.

(3) Project planning

Taking all the above into consideration, study a necessary facility preparation plan and create a general project plan. Then, prepare a rough estimate of construction expenses.

Table 4.2.2 Site Survey Flow

Study Item	Contents of Survey	Reference Materials
Water source location	**<u>Topographical and geological surveys</u>** 1) Topographical survey Collection of existing topographical maps and topographical mapping (scale 1:5,000) of the aquifer distribution area 2) Physical prospecting Shape of hydraulic basement 3) Boring survey Shape of hydraulic basement and permeability of aquifer and hydraulic basement	Purchase topographical maps issued and supervised by the geographical information management bureau of the government. Place orders from professional organizations or agencies. ● Topographical mapping ● Physical prospecting ● Boring survey
	<u>Meteorological and hydrological surveys</u> 1) Meteorological survey Collection of data on daily rainfall, evaporation, temperature and humidity, and rainfall observation 2) Surface water flow rate survey Data collection and river flow rate observation 3) Groundwater level observation Continuous observation and batch water measurement 4) Groundwater use survey 5) Water survey Electric conductivity measurement, etc.	Purchase statistics issued by the geographical information management bureau of the government. Obtain reports created by the water resources management bureau of the government. Obtain data from a meteorological station. Hold hearing surveys. Newly install observation facilities and gages. ● Daily rainfall observation ● Groundwater level observation, etc.
Environmental changes **Exploitable water quantity**	**Hydraulic analysis** 1) Water balance analysis Rough calculation of water balance using series tank model 2) Groundwater flow analysis Reproduction of hydraulics with three-dimensional difference model 3) Forecast calculation Environmental changes and exploitable water quantity 4) Study of subsurface dam operation plan	Place orders from professional organizations or agencies.
Supply and distribution method **Project expenses**	**Feasibility examination for subsurface dam development** 1) Construction technology survey 2) Study of farm village improvement plan Distribution destination development planning 3) Project planning Facility preparation and general project planning	Purchase or obtain statistics, reports, drawings, and reference materials issued and supervised by the government and regional administrative organizations. Hold hearing surveys.

4.3 Case Survey: Ketes, Indonesia

4.3.1 Selection of the survey area

From the six candidate sites for subsurface dam construction selected by the preliminary survey, Ketes on the island of Bali was chosen for the site survey. The Water Resources Research Center, a governmental research institution of Indonesia, had already conducted a grouting test and the hydrological and geological data available for that site was more extensive than for the other sites. Ketes is a catchment area of the Ketes River located in the eastern part of the island. The entire catchment area belongs to Bunutan, Karangasem in Bali.

Figure 4.3.1 Location Map of the Survey Area

View of the Ketes River from the coast

Downstream catchment area of the Ketes River

4.3.2 Outline of the survey area

The preliminary survey clarified the following:

(1) Meteorology

The climate on the island of Bali can be divided into the rainy season and the dry season. The rainy season is from November until April when the island is stricken by northwestern monsoons. The dry season is from May, when southeastern monsoons begin to appear, until October. Even on the same island, annual precipitation differs from 1,000 to 3,000 mm depending on the particular spot. Precipitation is lowest in the northeastern part of the island, including Ketes.

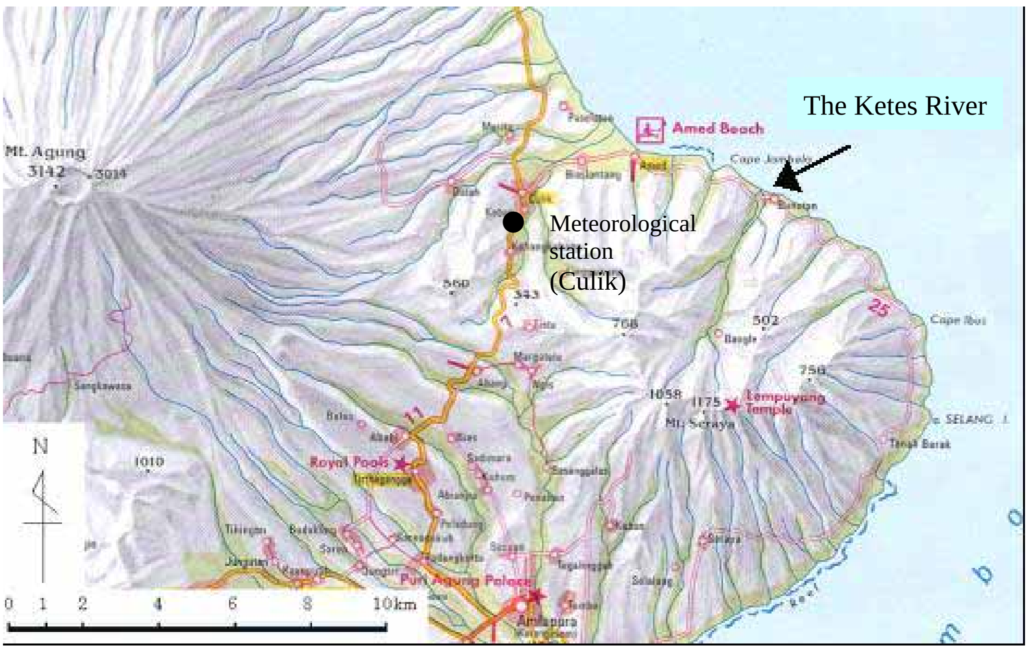
The temperature is almost constant throughout the year. The minimum mean temperature is about 22°C, the maximum mean temperature is about 34°C, and the mean humidity ranges from 77 to 86%.

(2) Topology and geology

The rivers flowing from the mountains forming the northern backbone of the island are as short as 5 to 10 km and dry up in the dry season. The catchment area of the Ketes River consists of a valley, most widely dissected in the northeastern part of the island, and also a developed alluvial fan.

Near Ketes are Mt. Agung (3,142 m high) and Mt. Seraya (1,211 m high). Both mountains are volcanoes formed during the Quaternary Period and the line linking them is a watershed separating the island of Bali into the northern and southern areas. Mt. Seraya is located at the furthest upstream position of the catchment area of the Ketes River. The entire area is thickly covered with ejecta (lava and ashes) from both volcanoes. The alluvial fan is formed about 2 km upstream from the river mouth. The valley width gradually increases toward the sea but does not exceed about 700 m even at the coast.

Figure 4.3.2 Water System, Eastern Bali Island

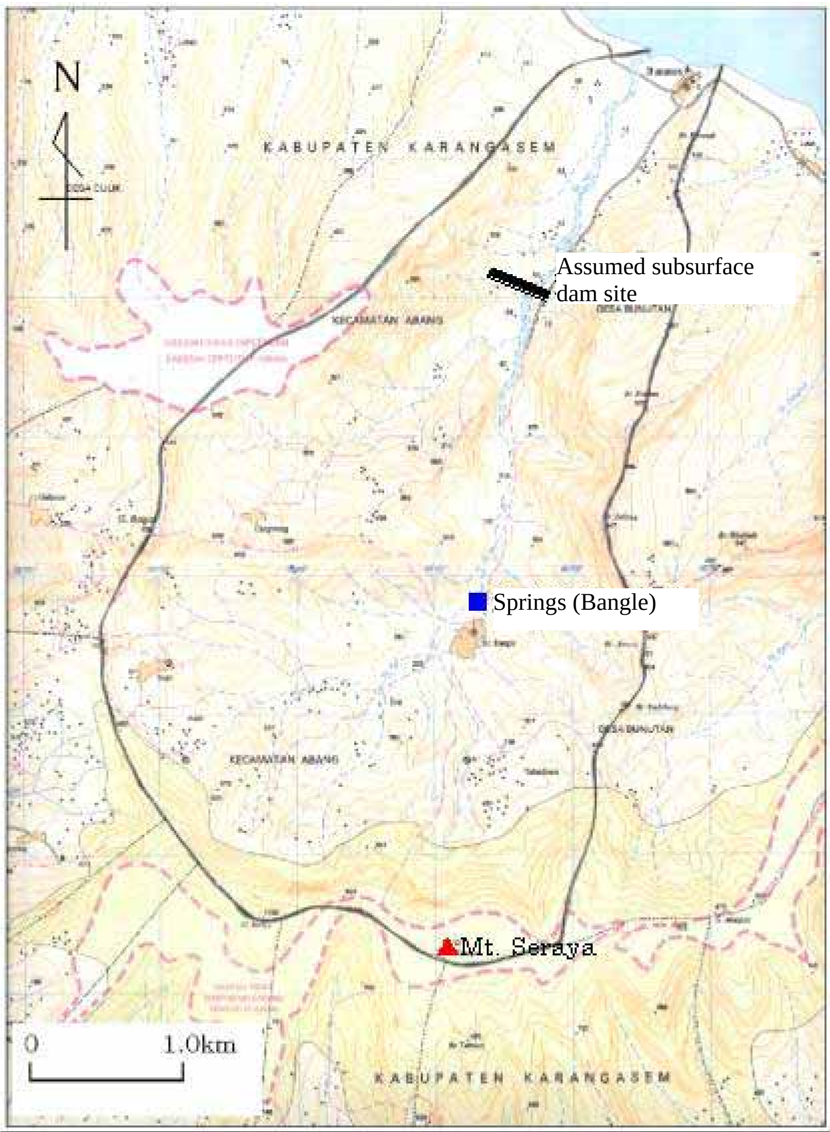


(3) Water environment

The alluvial fan has riverbed sediments distributed which bury the valley, forming a powerful aquifer. In the rainy season, this aquifer becomes almost saturated with groundwater that often overflows into the river. In the dry season, however, the groundwater level gradually falls and the river runs dry. About 4 km upstream from the coast, there is a spring that never runs dry throughout the year.

The subsurface dam site is assumed near the surface of the alluvial sector about 2 km from the coast.

Figure 4.3.3 Topographical Map of the Survey Area (Catchment area of the Ketes River)



4.3.3 Topographical and geological surveys

(1) Topographical survey

There is already a topographical map [1:10,000] covering the entire catchment area of the Ketes River. The contour pitch is 25 m.

In this survey, a new topographical map [1:5,000] was created covering the area within 3 km of the river mouth. The contour pitch is 2 m and even fine riverbed topography is reproduced.

(2) Electric prospecting

Electric prospecting was conducted about 2 km from the coast. This area is located at an upper part of the alluvial fan and the valley expands in an apron shape toward the downstream. The Water Resources Research Center conducted a boring survey three times from 1991 to 1993 (also as a grouting test). The alluvium was found to be 30 m thick.

Electric prospecting was conducted with survey lines covering an area of 600 m parallel to the river and about 300 m in the orthogonal direction. The subsurface (to about 60 m deep) geology was estimated by employing pole-pole array (Schlumberger array). This method is used for estimating the subsurface resistivity distribution by installing electrodes on the surface and applying an electric current into the ground. Measuring points were 60 in total.

The prospecting clarified a structure roughly consisting of three layers. This could be estimated because a low-resistivity layer of 50 to 500 Ωm is sandwiched between the two high-resistivity layers of 500 to 5,000 Ωm and 100 to 10,000 Ωm. The low-resistivity layer is harmonious with the existence of strongly weathered volcanic rocks formerly confirmed by a boring survey and estimated to be equivalent to the surface of volcanic rocks. These indicate that the structure consists of layers of riverbed sediments (aquifer), strongly weathered volcanic rocks, and hard volcanic rocks from the top.

(3) Boring survey

By assuming one of the electric prospecting survey lines as the tentative subsurface dam site, a boring survey was conducted as shown in Table 3.3.1 to verify a more accurate geologic structure and hydraulics characteristics.

(a) Excavation

Core boring was conducted at four points (JB-1 to JB-4) and non-core boring at two points (JW-1 and JW-2). A pumping test was performed after excavation. The heaped cores were observed as follows:

Table 4.3.1 Outline of Boring Survey

No.	Point	Depth	Bore	Remarks
JB-1	Dam downstream	40 m	86 mm	Water level observation hole
JB-2	Dam axis right	25 m	86 mm	Water level observation hole
JB-3	Dam axis left	25 m	86 mm	Water level observation hole
JB-4	Dam upstream	35 m	86 mm	Water level observation hole
JW-1	Dam upstream	35 m	150 mm	Water level observation (pumping test) hole
JW-2	Dam downstream	30 m	200 mm	Water level observation (pumping test) hole

At any point, the layer changes from riverbed sediments (or “collapse” sediments: talus) to volcanic breccia and hard volcanic rocks from the top. However, it is difficult to find clear changes of facies. One of the factors is that the gravel forming the riverbed sediments is volcanic rock.

The basement volcanic rocks can also be divided into hard portions and rubble. The rubble is difficult to distinguish from riverbed sediments because it contains sand or other matrices and is weathered.

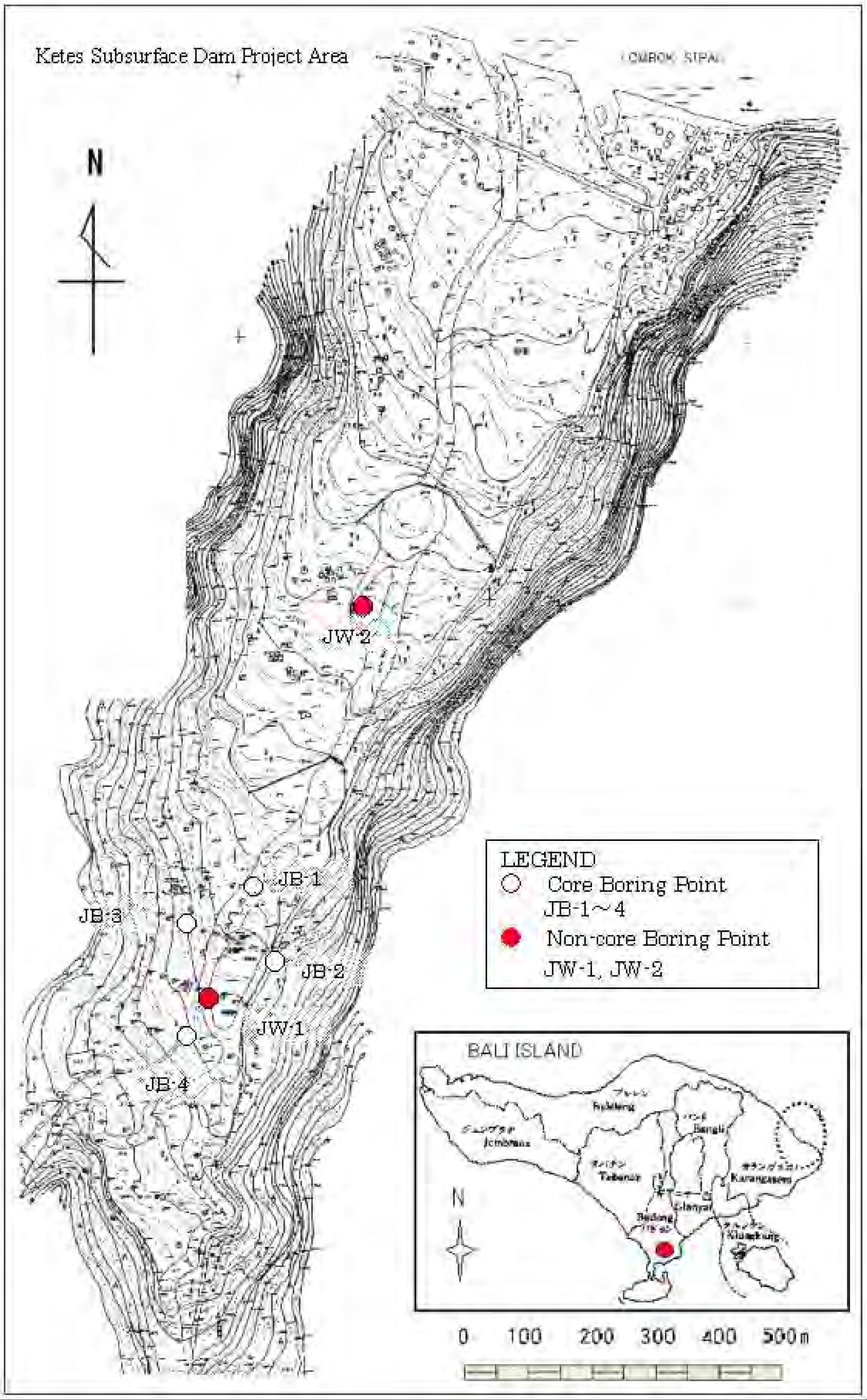
The stability of a bore wall after excavation was found to increase obviously from a certain depth. The bore wall is unstable in riverbed sediments and stable in volcanic rocks. This is also endorsed by their origins.

The subsurface dam axis is assumed on the line linking JB-2 and JB-3. The Water Resources Research Center conducted a boring survey (GT-1: also as a grouting test) in the middle of the boring points or the center of the valley and found that the alluvium was about 30 m deep. Similar results were also obtained at JB-1. To the contrary, the lower volcanic rocks were about 15 m deep at JB-2 and JB-3 about 50 to 75 m away from the center of the valley. Considering this, the basement is close to a V-shaped valley rather than a U-shaped valley.

JW-1 and JB-4 are located at the center of the valley and only about 200 to 300 m upstream of JB-1. However, the basement depth is as much as 15 m shallower than at JB-1. This indicates that the basement inclination in the upstream-downstream direction is sharper than the surface inclination.

JB-3 can be estimated as a talus distribution area because the upper sediments of volcanic rocks are clay-mixed conglomerates.

Figure 4.3.4 Location Map of the Boring Survey



This clarifies the volume of the reservoir layer of the assumed subsurface dam where only the riverbed sediments are expected as a reservoir. Taking the valley shape into consideration, the volume is about 500,000 m^3. If the effective porosity is about 10 to 20%, a reservoir capacity in the range of 50,000 to 100,000 m^3 can be expected.

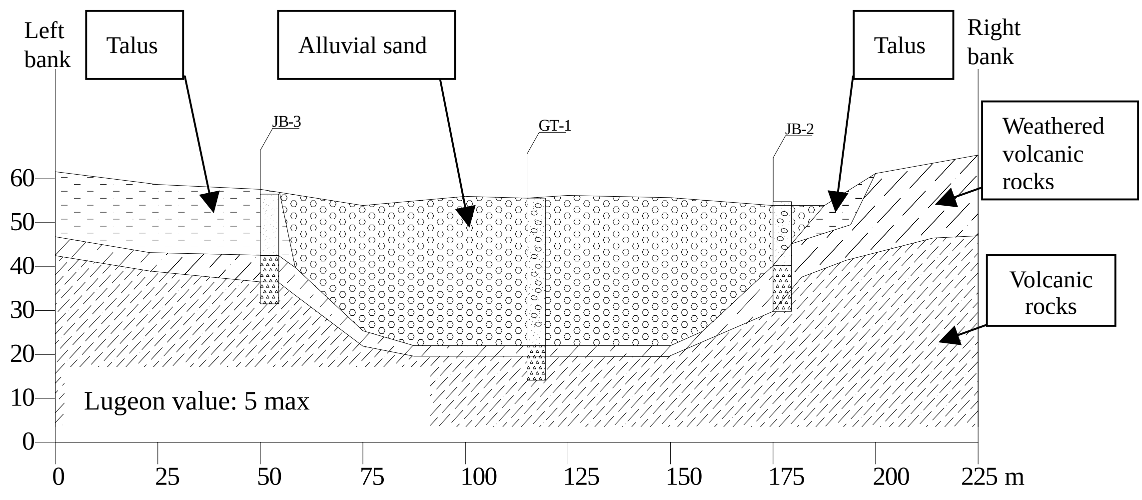
At JW-2, a boring survey was conducted to check the alluvium thickness and also the annual fluctuation of groundwater level by groundwater level observation after boring excavation. By non-core boring, the ground was dug to 30 m deep so that the maximum depth would not exceed the seawater level.
At all points, the layer consisted of riverbed sediment and the basement could not be reached.

(b) Field permeability test
A field permeability test was conducted on all boreholes. As a rule, this comprised a constant head permeability test for the aquifer and a Lugeon test for the basement. As mentioned before, the border between aquifer and basement was judged from the stability of a bore wall. More specifically, the permeability of riverbed sediments and talus was evaluated by a constant head permeability test and that of volcanic rocks was evaluated by a Lugeon test.

Riverbed sediments show high permeability where the hydraulic conductivity 10^{-2} is 5×10^{-3} cm/sec. Talus at JB-3 and others show lower permeability than riverbed sediments where the hydraulic conductivity is 10^{-3} to 10^{-5} cm/sec. This also conforms to the tendency of clay confirmed by core observation in the boring survey.

Volcanic rocks also show high permeability of 40 to 80 Lu (hydraulic conductivity: 10^{-3} – 5×10^{-4} cm/sec) at the upper part. In general, the lower hard portions show low permeability. At JB-1, bedrock of 5 Lu or less (hydraulic conductivity: about 5×10^{-5} cm/sec) was found at 35 m or deeper.

Figure 4.3.5 Geologic Profile of the Assumed Subsurface dam Axis



4.3.4 Meteorological surveys

(1) Meteorological survey

The Culik Meteorological Station is 7 km to the north of Ketes. The following data was collected:

- Daily rainfall for 10 years from 1990
- Temperatures (minimum, maximum, and mean) of five years from 1995

Table 4.3.2 Rainfall Recorded at the Culik Meteorological Station by Month (Unit: mm)

Year/ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
1990	427	195	425	183	235	89	53	71	68	92	7	327	2,172
1991	567	545	57	217	9	5	121	1	7	1	77	183	1,790
1992	243	755	165	417	25	8	55	23	95	187	220	201	2,394
1993	349	641	157	74	63	141	10	55	16	181	80	234	2,001
1994	353	272	563	266	45	2	15	1	1	1	44	326	1,889
1995	217	483	379	371	75	112	35	3	37	125	237	364	2,438
1996	371	415	284	53	31	7	5	66	8	361	127	314	2,042
1997	460	507	50	79	98	33	166	70	0	4	98	148	1,713
1998	456	231	218	194	151	74	113	118	275	181	156	300	2,467
1999	557	589	545	378	34	20	55	68	15	229	95	281	2,866

The annual mean rainfall at Culik exceeds 2,000 mm. Culik is in the catchment area on the north of Ketes but near a pass of less than 500 m in altitude between the volcanoes of Mt. Agung (3,142 m) and Mt. Seraya (1,175 m). Therefore, Culik may be affected by the climate of the Indian Ocean beyond the pass. The rainfall is at its peak during January to February when the monthly mean rainfall is 200 to 300 mm and as low as 5 mm or less in average from June to September. There is no clear border between the rainy season and the dry season but the daily rainfall and the rainfall frequency change gradually. Even in the dry season, it often rains.

Two rainfall observation points were set in Ketes (catchment area of the Ketes River). One point was near the Bangle springs and the other was near the assumed subsurface dam site. The points are only 2 km away from each other but set because the rainfall tendency was judged to be different between the mountain side and the sea side.

The temperature is constant throughout the year. The minimum mean temperature is about 22°C, the maximum mean temperature is about 34°C, and the mean humidity is about 77 to 86% annually.

(2) Surface-water flow rate survey

Throughout the year, a sizable amount of surface water can always be seen only near Bangle, about 4 km upstream from the coast. There is not only a river but also a channel that gathers spring water from the mountain-side slope for agricultural use. A measuring weir was prepared in this channel and the flow rate was measured. The observation was continued for one year.

The Bangle springs are located at the conversion point of the river gradient of the Ketes River and also at the end of the talus sediments distribution area at the foot of Mt. Seraya. In the catchment area, this is where the surface and the groundwater level are closest to each other. The surface water will never run dry because of perpetual water leakage from the rear talus sediments, which is regarded as a good groundwater reservoir layer. The surface water near the Bangle springs is supplied to the downstream area as river water or riverbed water.

The flow rate into the Ketes River was observed at three downstream points of the Bangle springs. The surface water could be observed on more days at an upstream observation point.

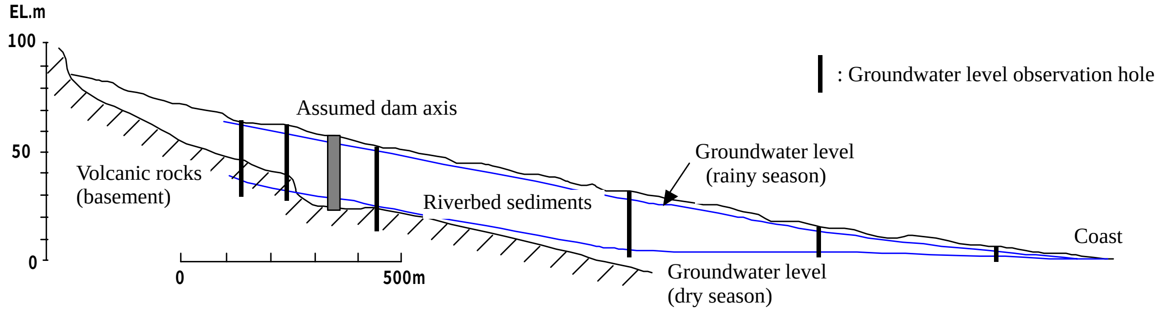
(3) Groundwater level observation

In the catchment area of the Ketes River, the valley width is small but the alluvial fan grows at about 2 km upstream from the coast. Riverbed sediments are distributed here, forming a powerful aquifer. In the rainy season, this aquifer becomes almost saturated with groundwater that may overflow into the river. In the dry season, the groundwater level gradually falls and the river runs dry.

The maximum thickness of the aquifer exceeds 30 m. The groundwater level is fixed (altitude: 0 m) near the coastline throughout the year but the annual fluctuation width (difference between the rainy season and the dry season) grows in the upstream direction. To check this trend of the groundwater level, six boreholes from the boring survey were used for groundwater level observation. One local resident is now measuring the groundwater level manually once a day.

In November, at the end of the dry season (beginning of the rainy season), the groundwater level reaches the annual minimum reservoir level. In some places, the groundwater level falls to about 30 m below the surface. During February to March when there is the greatest amount of rainfall in the year, the groundwater level rises close to the surface and the groundwater overflows to the river. Figure 4.3.6 depicts annual groundwater level fluctuation. From the rainy season to the dry season, the groundwater level falls simultaneously in a translation form and stops near the seawater level. In January 2002, the groundwater level dropped close to the seawater level, up to about 1 km upstream from the coast (around JW-2).

Figure 4.3.6 Profile of the Downstream Area of the Ketes River



4.3.5 Hydraulic analysis

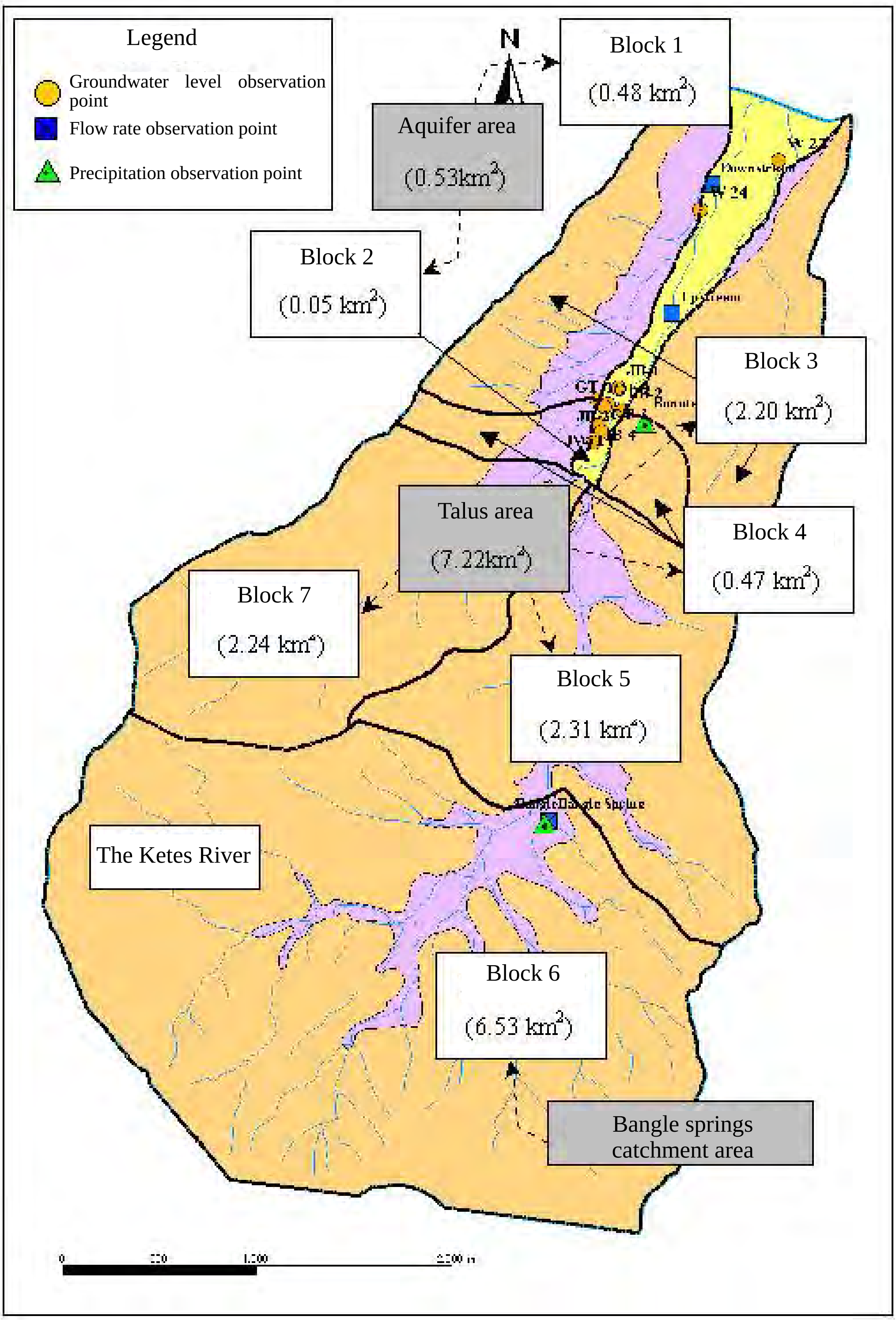
(1) Water balance analysis

Create a numeric model (series tank model) to roughly reproduce water circulation in the catchment area of the Ketes River.

(a) Analytical flow

1) Divide the catchment area into seven blocks (Figure 4.3.7). By considering each block as a tank, create a three-stage structure consisting of surface, non-saturated soil, and saturated soil (aquifer).
2) For the series tank model calculation, set analytical parameters (surface area, bottom altitude of the aquifer, sectional area, distance between adjacent tanks, effective porosity, saturated hydraulic conductivity, etc.).
3) Estimate and calculate the evapotranspiration in time series.
4) Link the aquifers of adjacent tanks using the flow equation of Darcy’s law.
5) Enter rainfall and intake data and calculate the inflow and runoff in each block and the groundwater level in the aquifer distribution area in time series.
6) Compare the above calculated values with the observed values of river flow rate and groundwater level.
7) Adjust the parameters (of low accuracy) related to evapotranspiration and aquifer and calculate the values again to verify correlation with the observed values.

Figure 4.3.7 Block Diagram of the Tank Model



(b) Model creation notes

- Runoff from the Bangle springs

A non-permeable basement covered with talus sediments is located around the Bangle springs about 4 km upstream from the coast. The talus sediments store rain and the runoff water from there is adjusted. Create a model based on this image.

At the Bangle springs, groundwater wells up because the groundwater level is equal to the surface. Considering the fact that the springs never run dry throughout the year, the permanent existence of a certain depth of groundwater should be set as a condition. For convenience, a break of the talus sediment distribution at the Bangle springs was set for exposure of the non-permeable basement. In other words, the groundwater welling up from the talus sediments on the upstream side of the springs all runs off to the surface. The runoff water permeates into the talus sediments distributed on the downstream side or flows over the surface.

The area and thickness of talus are not known. For consistency with the quantity of groundwater welling up from the spring, however, adjust and calculate the area and thickness in the model verification. The basement of volcanic rocks is handled as non-permeable bedrock. In other words, rain does not permeate into the volcanic rocks but instead flows over the basement.

- Charging to the aquifer area

The talus spreads continuously along the river from the Bangle springs to the downstream aquifer area. Surface water and groundwater from the talus area flow into the reservoir area of the assumed subsurface dam. After flowing to the surface in the aquifer area, the surface water partially permeates into the ground and the rest runs off the surface. The groundwater flows directly into the aquifer area. Of the inflow water from the talus area, water that permeated from the surface and water that directly flowed in as groundwater form groundwater charge into the aquifer area.

- Groundwater in the aquifer area

The aquifer area is divided into two blocks with the assumed subsurface dam site in between. The downstream-side block surface extends about 2 km along the Ketes River and the altitude difference is 50 m. The groundwater level has almost the same gradient as the surface. The groundwater flows under the influence of this gradient.

The groundwater level on the coast is fixed at 0 m. The groundwater flows into the sea in the end.

Figure 4.3.8 Concept of Water Circulation Mechanism

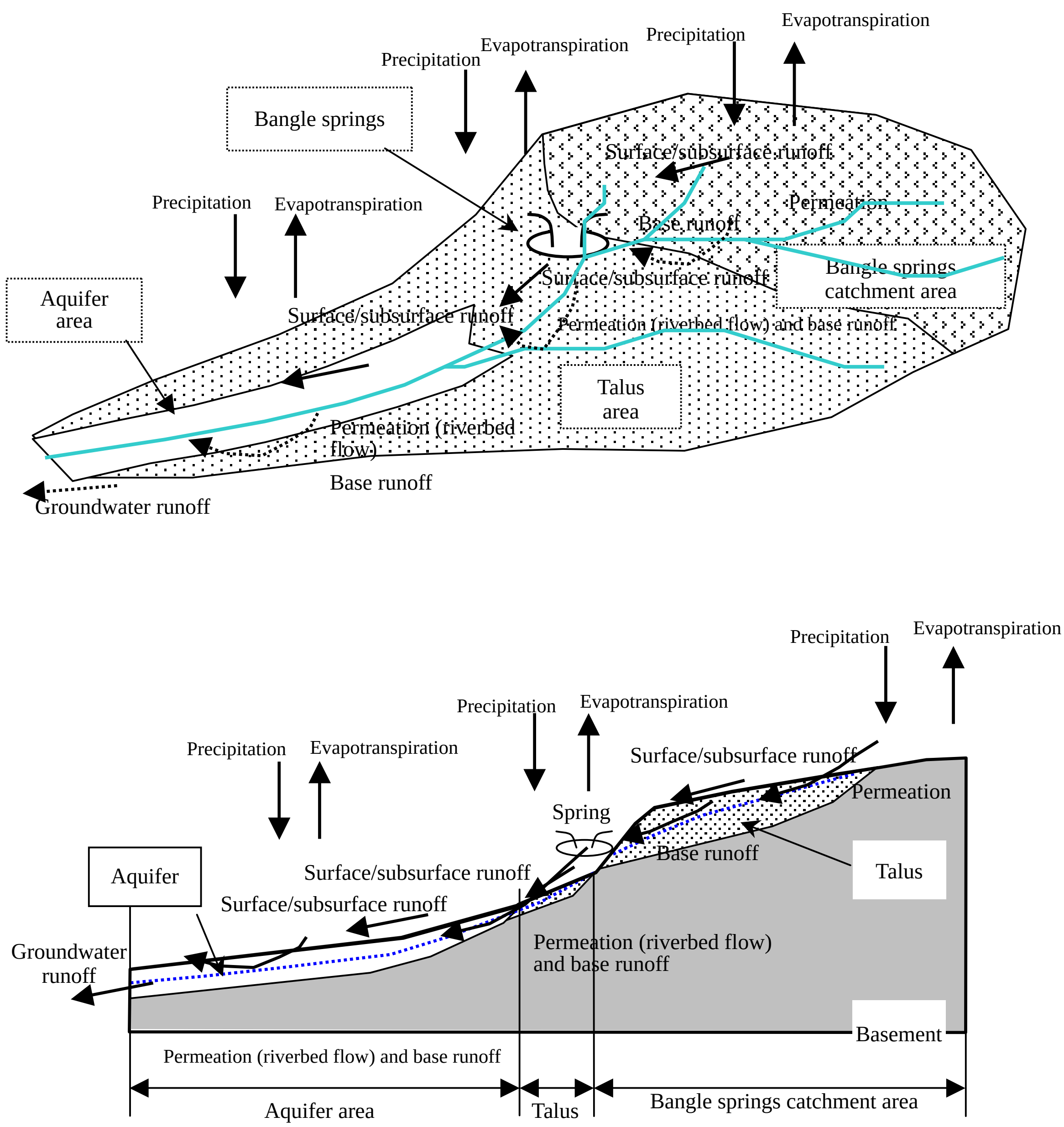


Figure 4.3.9 Concept of Groundwater Flow Rate Calculation Method

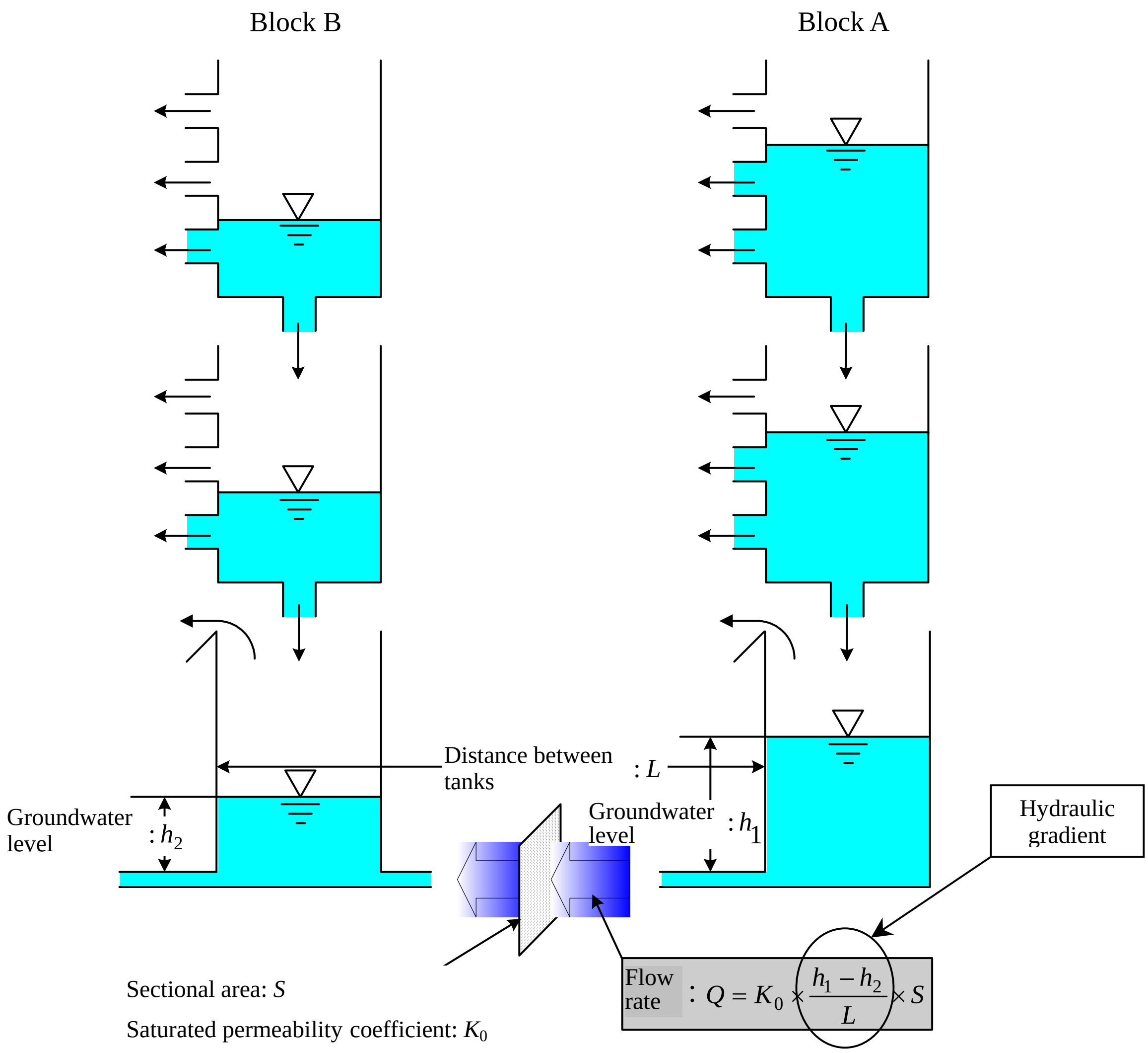
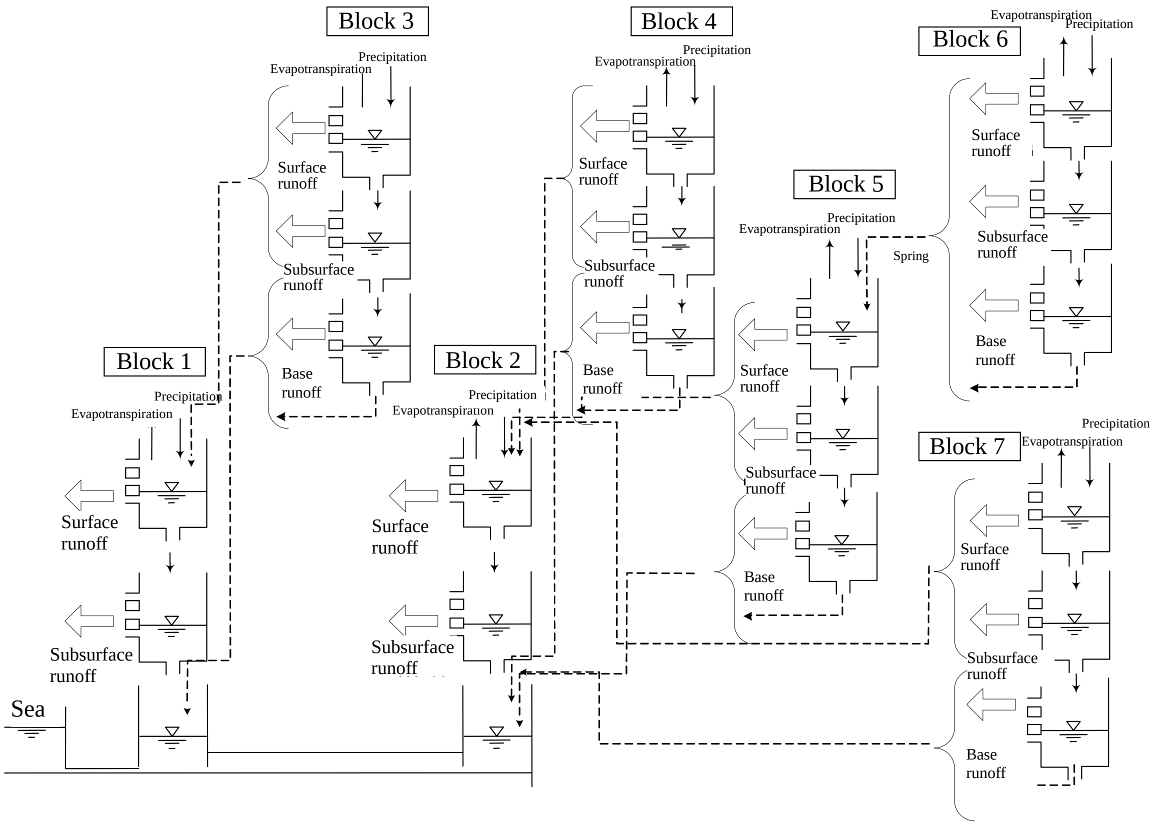


Figure 4.3.10 Tank Model Structure



(c) Study of parameters for model creation and analysis

- Rainfall

The daily rainfall observation data of Culik, near the survey area, was used.

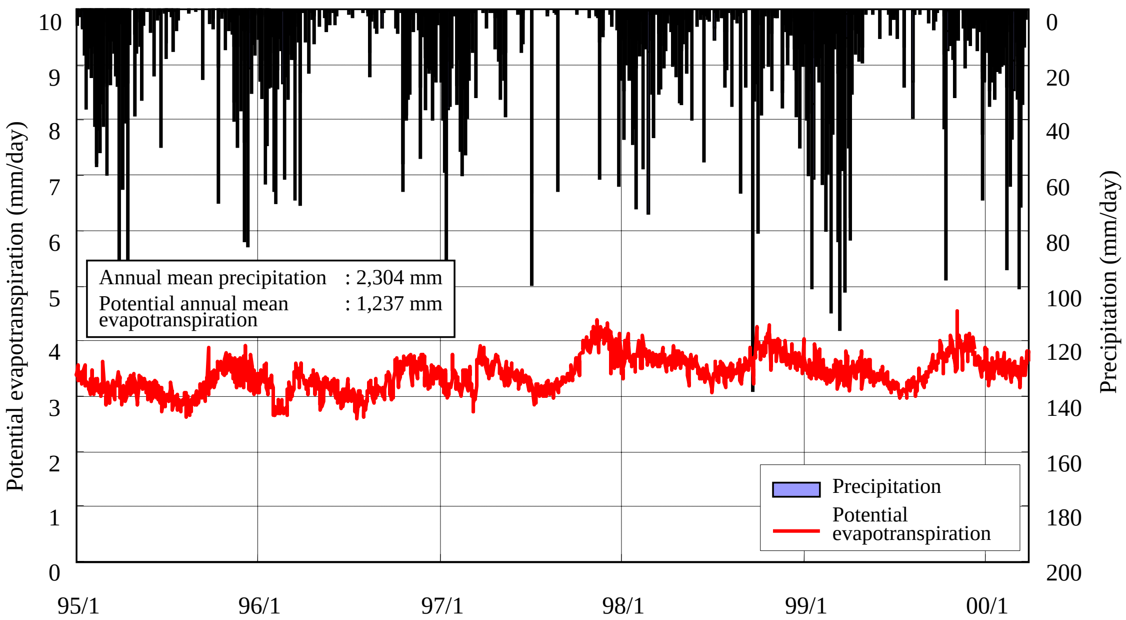
- Evapotranspiration

From temperature data observed at Culik, potential evapotranspiration was calculated using the Hamon equation. The annual total evapotranspiration will be about 1,300 mm in average. The daily potential evapotranspiration is assumed not to fluctuate greatly throughout the year.

Hamon equation: $E_p = 0.14(N/12)^2 P_t$

E_p: Daily potential evapotranspiration (mm/day), N: Possible duration of sunshine (hr), P_t: Saturated absolute humidity at daily mean temperature (g/m^3)

Figure 4.3.11 Rainfall and Evapotranspiration Data Used for Analysis



- Modeling the talus area

The water observed at the Bangle springs is only part of the water welling up. The actual quantity of spring allows only for estimation. When the flow rate of the nearby river was measured by eye, it was several times that of the data-measured channel. Therefore, the actual flow rate was regarded as three or four times the observed value.

Every talus in the catchment area has a reservoir function. To calculate the quantity of water running off from the talus area, the parameter prescribing the runoff quantity from the second tank to the third tank in the same block was consequently adjusted. This parameter was set in proportion to the ratio of the talus area to the catchment area. The calculation formula is as follows:

$A' = A \times (S_2 \div S_1) \div 0.085$

A': Second-stage bottom-hole parameter, A: Second-stage Bangle springs value (0.065), S_2: Talus area, S_1: Talus catchment area

- Modeling the aquifer area

As Figure 4.3.9 shows, the aquifer tanks of Blocks 2 and 1 were linked to allow groundwater flow according to Darcy's law. Table 4.3.3 lists the parameters used for analysis.

Values practical in terms of facies were given for the saturated hydraulic conductivity and effective porosity, both of which were set uniform in the block. The distance from an adjacent tank is between the points where the measured and calculated values of groundwater level are compared for verification. The cross section between Blocks 2 and 1 is based on the sectional view on the assumed dam axis and its area increases or decreases as the groundwater level rises or falls.

Table 4.3.3 Parameters Used for Series Tank Model Calculation

Block name	Adjacent tank name	Tank altitude (m)		Saturated hydraulic conductivity (cm/sec)	Effective porosity	Distance from adjacent tank (m)	Sectional area (m^2)
		Bottom	Top				
Block 1	Sea surface	-30.0	10	1.0×10^{-2}	0.1	300	30,000
Block 2	Block 1	-20.0	60	3.4×10^{-2}	0.1	1,500	Depending on water level

(d) Model verification

- Flow rate of the Bangle springs

Figure 4.3.12 compares the estimated values calculated from measured values with the calculated values of the tank model. In this collation of only one year, the values match comparatively well in the dry season but show significant discrepancies in the rainy season. However, the values are rough. For example, the values estimated from the measured values are in simple proportion to the channel flow rates. There will be no question if the river flow rates near the springs increase greatly in the rainy season with no connection to the channel flow rates.

Figure 4.3.12 Calculated Quantity of Spring Water in the Bangle Springs Catchment Area

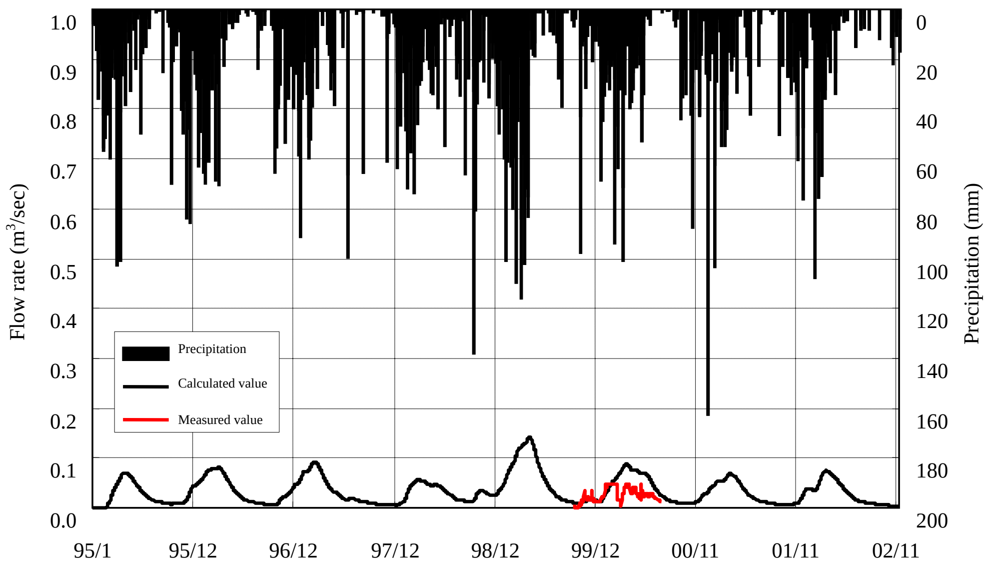


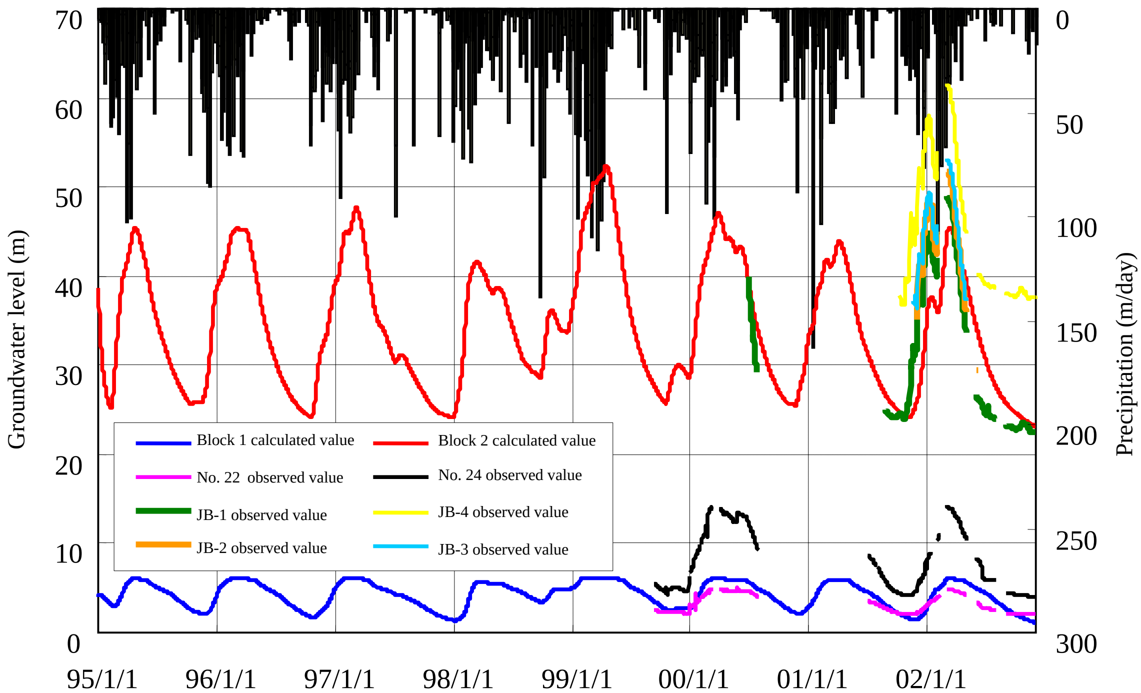
Table 4.3.4 Calculated Water Balance in the Bangle Springs Catchment Area (×1,000 m^3)

Year	Precipitation	Evapotranspiration	Surface/sub surface runoff	Groundwater charge	Base runoff quantity	Storage (Groundwater charge - Base runoff)
1995	15,901	4,497	9,840	1,225	776	449
1996	13,336	3,615	8,571	1,140	1,128	12
1997	11,172	3,858	6,428	807	1,024	-217
1998	16,112	6,053	8,805	1,160	988	172
1999	18,719	4,173	12,786	1,559	1,662	-103
2000	15,166	4,311	10,016	1,323	1,259	64
2001	13,403	4,672	7,477	928	892	36
Annual mean (In mm)	14,830 (2,271)	4,454 (682)	9,132 (1,398)	1,163 (178)	1,104 (169)	59 (9)

- Groundwater level

The groundwater level was continuously observed (once a day) not only at the observation holes prepared by the boring survey in this survey but also at two points near the coast (Nos. 22 and 24: see Figure 4.3.7). The calculated values of Block 1 are based on the groundwater level at No. 22 and those of Block 2 are based on the groundwater level on the assumed dam axis.

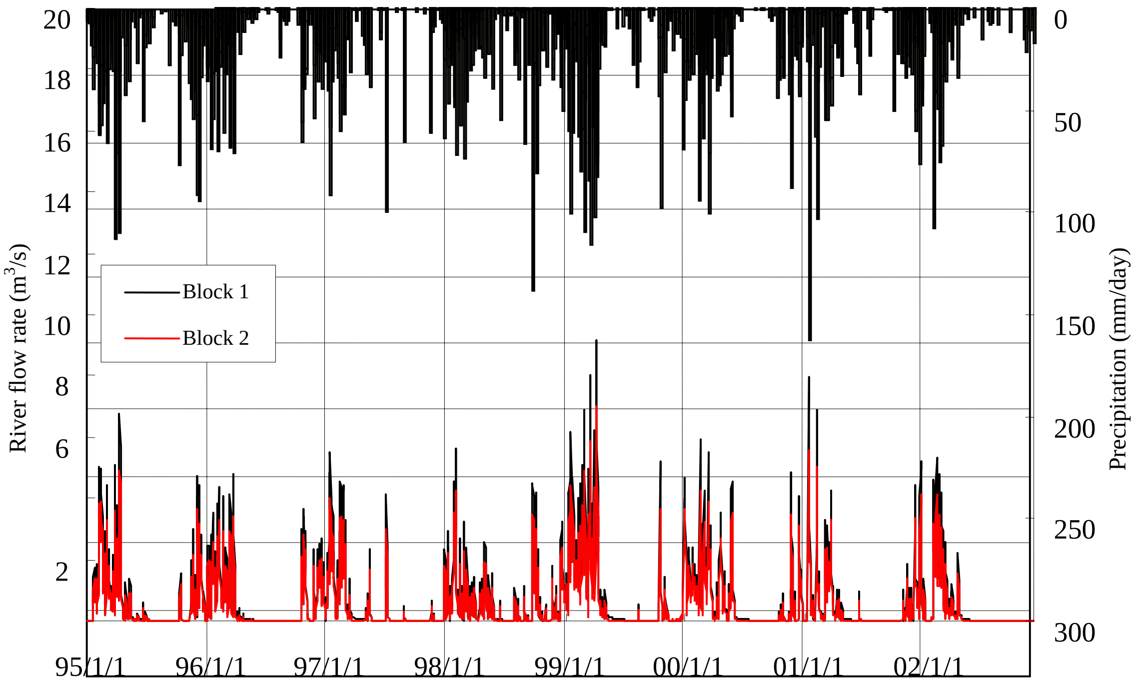
Figure 4.3.13 Calculated and Measured Groundwater Levels in the Aquifer Area



● River flow rate

The figure below shows the calculated river flow rates at the furthest downstream points of Blocks 1 and 2.

Figure 4.3.14 Calculated River Flow Rates in the Aquifer Area



● Rough water balance

Table 4.3.5 and Figure 4.3.15 show the rough water balances obtained by model calculations. Table 4.3.5 also gives the values in 1997 when drought was recorded.

Table 4.3.5 Calculated Water Balances in the Aquifer Area

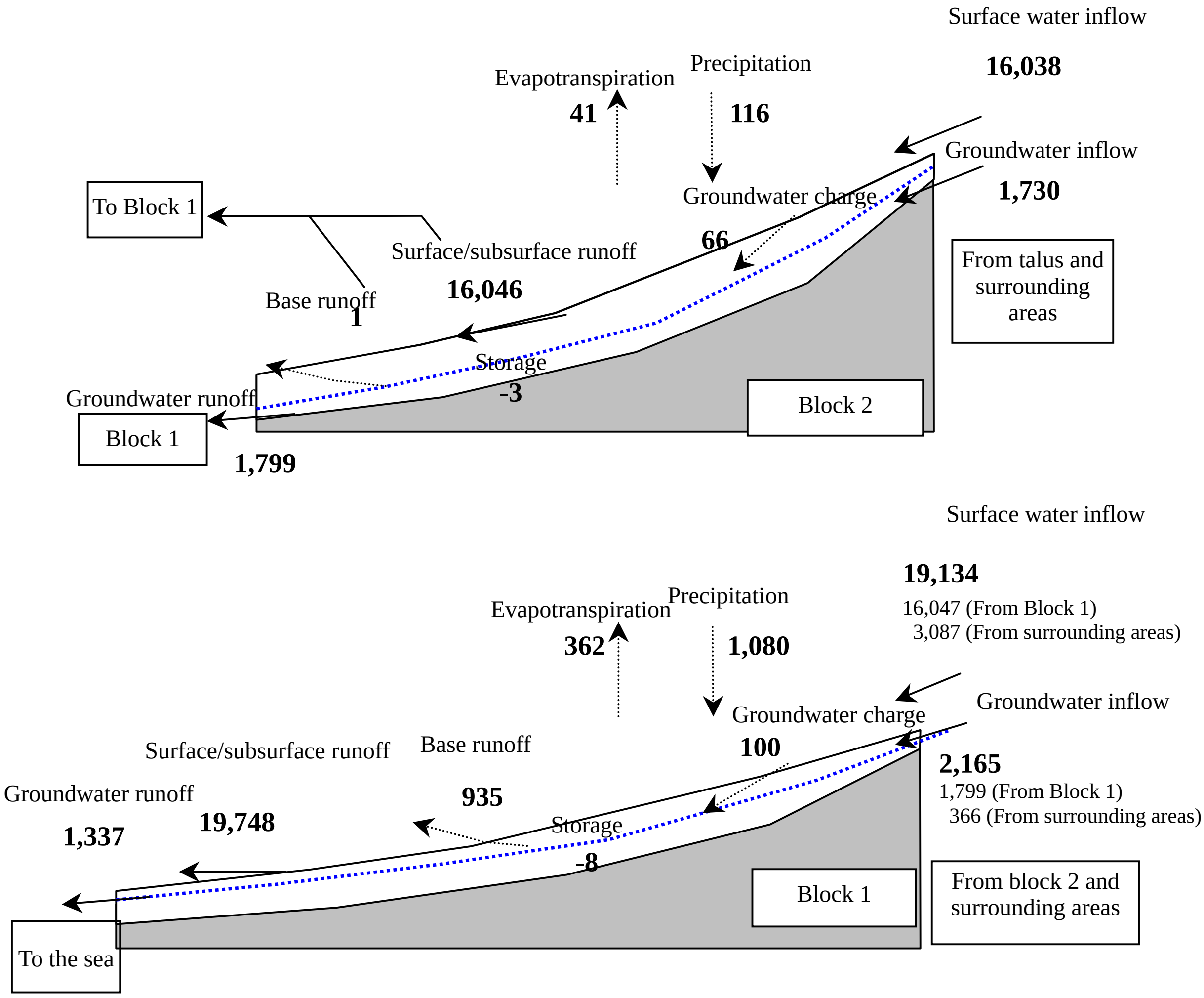
Block 1 (×1,000 m^3)

	Precipitation	Surface water inflow	Evapotranspiration	Surface/subsurface runoff	Groundwater charge	Groundwater inflow	Base runoff	Groundwater runoff	Storage
Annual mean (In mm)	1,080 (2,280)	19,134 (40,410)	362 (764)	19,748 (41,707)	100 (211)	2,165 (4,571)	935 (1,974)	1,337 (2,824)	-8 (-16)
1997 (In mm)	813 (1,712)	13,454 (28,324)	312 (657)	13,886 (29,234)	70 (147)	1,993 (4,195)	923 (1,944)	1,309 (2,755)	-169 (-356)

Block 2 (×1,000 m^3)

	Precipitation	Surface water inflow	Evapotranspiration	Surface/subsurface runoff	Groundwater charge	Groundwater inflow	Base runoff	Groundwater runoff	Storage
Annual mean (In mm)	116 (2,280)	16,038 (314,475)	41 (802)	16,046 (314,636)	66 (1,301)	1,730 (33,923)	1 (17)	1,799 (35,268)	-3 (-61)
1997 (In mm)	88 (184)	11,275 (23,738)	37 (77)	11,280 (23,747)	47 (99)	1,534 (3,230)	0 (0)	1,658 (3,490)	-77 (-161)

Figure 4.3.15 Analyzed Model Water Balances (1,000 m^3/year)



(2) Groundwater flow analysis

Create a numeric model (three-dimensional difference model) to reproduce groundwater-level plane distribution and its fluctuation in the aquifer area, including the assumed subsurface dam site.

(a) Analytical flow

1) Based on the results of topographical and boring surveys so far, estimate the geologic structure and digitize the topography and altitude of the aquifer base.
2) For analysis using the plane three-dimensional difference model MODFLOW, divide the plane into 30×30-m square grids. Each grid consists of several layers of different permeability.
3) For the effective porosity and hydraulic conductivity of each grid layer, basically adopt numeric values that do not conflict with the parameters used for the series tank model.
4) Enter the groundwater charge data calculated from the rainfall and series tank model and calculate the groundwater level in each grid.
5) Compare the above-calculated values with the measured groundwater levels.
6) Adjust the parameters related to aquifer until the calculated values become close to the observed ones. Make sure that the parameters do not conflict with the ones used for the series tank model.

Calculate the values again and verify their correlation with the measured values.

(b) Model creation notes

- Expression of groundwater level distribution

An outline of the water balance of the general catchment area can be obtained by analysis using the series tank model. However, the series tank model expresses the groundwater level only at a representative point in the divided analysis block. For the aquifer area in the downstream region of the Ketes River, the groundwater level is expressed at two points only. One is a point directly upstream from the assumed subsurface dam site and the other is about 300 m inland from the coast. The distance between the points is only 1.5 km but the groundwater level differs greatly from 20 to 40 m.

The aquifer area becomes wider in the downstream direction, which greatly affects the groundwater flow due to dispersion in the aquifer or other. Under these circumstances, plane and time series changes of the groundwater level cannot be completely expressed by the series tank model. Therefore, the analytical software "plane three-dimensional difference model MODFLOW" was adopted for verification in fragmented analytical units.

- Expression of permeation and leakage

It is necessary to express water permeation and leakage through a hydraulic basement and a subsurface dam (cut-off wall). Since the groundwater level falls greatly in the dry season every year, it is difficult to maintain a significant water-level difference between the sides of a cut-off wall even if installed. The effects of the subsurface dam must be evaluated by subtracting the leakage.

- Layer classification

To avoid complicated calculations, the layer classification of the analytical model should be made as simple as possible. In 4.3.3, the geologic stratigraphy was roughly divided from the bottom into four layers: hard volcanic rocks, volcanic breccia (or strongly weathered volcanic rocks), talus sediments, and alluvial gravels. Considering the permeability, the volcanic breccia (or strongly weathered volcanic rocks) and talus sediments can be united into one because their hydraulic conductivities are about 10^{-4} cm/sec. Therefore, the geologic stratigraphy can be roughly divided by hydraulic conductivity into three layers: an alluvial sand layer of about 10^{-2} cm/sec, a layer of about 10^{-4} cm/sec, and a volcanic rock layer of about 5×10^{-5} cm/sec.

In the analytical model, the alluvial gravel layer was divided into the upper free-state aquifer and the lower free-state and confined-state mixed aquifer by considering the peak of the assumed dam site.

- Inflow to the subsurface dam reservoir area

For the inflow to the subsurface dam reservoir area, the numeric values obtained by water balance calculations with the series tank model are used. Volcanic rocks have hydraulic conductivity of about 5×10^{-5} cm/sec for certain permeability. In Ketes, volcanic rocks are regarded as a hydraulic basement and assumed to have no exchange with groundwater in the volcanic rocks throughout the catchment area.

- Boundary conditions

The boundary with the sea was set at the constant head of 0 m in altitude. A drainage canal was set on the surface by assuming the phenomenon where the groundwater level rises and the water wells up into the river.

(c) Study of parameters for model creation and analysis

- Digital hydraulic geologic structure

The geologic structure was roughly classified by hydraulic conductivity into three layers: an alluvial gravel layer of about 10^{-2} cm/sec, a layer of about 10^{-4} cm/sec, and a volcanic rock layer of about 5×10^{-5} cm/sec. Then, the altitude of each base was estimated from the results of the boring survey and digitized into contour data. Topographical map data [scale: 1:5,000] was also used.

- Structure of the analytical model

1) Adopted model

A model was created using "MODFLOW96" (U.S. Geological Survey numeric analysis software). During model creation, the fundamental functions of the software were extended to enable the following:

a) Steady state and non-steady state analyses

b) Plane two-dimension, cross-sectional two-dimension, quasi-three-dimension, and three-dimension analyses

c) Switching of free and confined states in the same stratigraphy for the aquifer, accompanying a state or water level change

d) Calculation of inflow and runoff between river and groundwater

e) Calculation of groundwater welling and drainage

f) Input of groundwater charge

g) Calculation of pumping from and pouring into a well

2) Structure

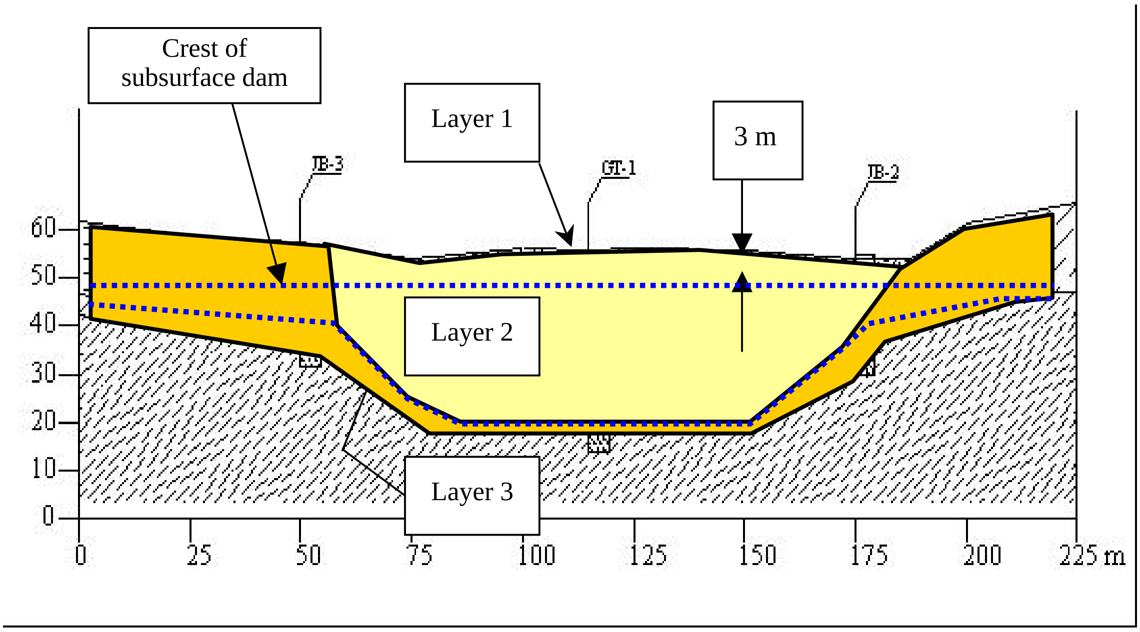
a) Classification of stratigraphy

Sequentially from the top, the stratigraphy was divided by hydraulic conductivity into a layer of about 10^{-2} cm/sec, one of about 10^{-4} cm/sec, and one of about 5×10^{-5} cm/sec. Then, the part higher than the crest of the subsurface dam was separated as a non-closure part. Table 4.3.6 summarizes the classification of stratigraphy. Switching is permitted to allow the upper layers, excluding Layer 1, to be handled as a confined-state aquifer if groundwater exists, and as a free-state aquifer if no groundwater exists.

Table 4.3.6 Stratigraphy Classification

Model Structure	Stratum Description	Aquifer Setting and Layer Thickness
Layer 1	Alluvial gravel layer, talus layer, and strongly weathered rubble	Free-state aquifer: 6 m (3 m on dam axis)
Layer 2	Alluvial gravel layer, talus layer, and strongly weathered rubble	Free-state and confined-state mixed aquifer: 24 m
Layer 3	Talus layer and strongly weathered rubble	Free-state and confined-state mixed aquifer: 5 to 15 m

Figure 4.3.16 Concept of Stratigraphy Classification



b) Target area of analysis and grid division

The aquifer area (alluvial gravel distributed area) and its adjacent talus area were set as the target of analysis. The area was divided into 30×30-m square grids.

c) Boundary conditions

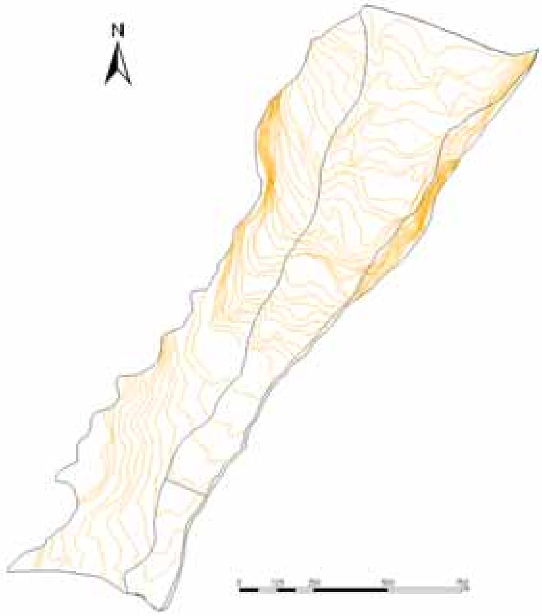
The boundary with the sea was set at the constant head of 0 m in altitude. For calculating groundwater welling up and drained, the surface of Layer 1 was set by assuming the phenomenon where the groundwater level rises and the water wells up into the river. The drainage calculation function was set for Layer 3 in the same way.

d) Charge data input

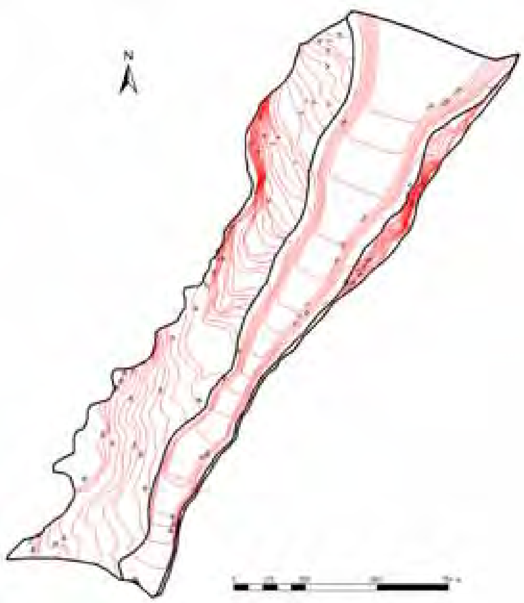
The results of water balance calculation using the series tank model were used.

Figure 4.3.17   Base Contour Map of Each Hydraulic Stratigraphy

Surface altitude (Layer 1 top face)



Layer 1 bottom face (Layer 2 top face) altitude
(Surface altitude - 6 m)



Layer 2 bottom face (Layer 3 top face) altitude

Layer 3 bottom face altitude

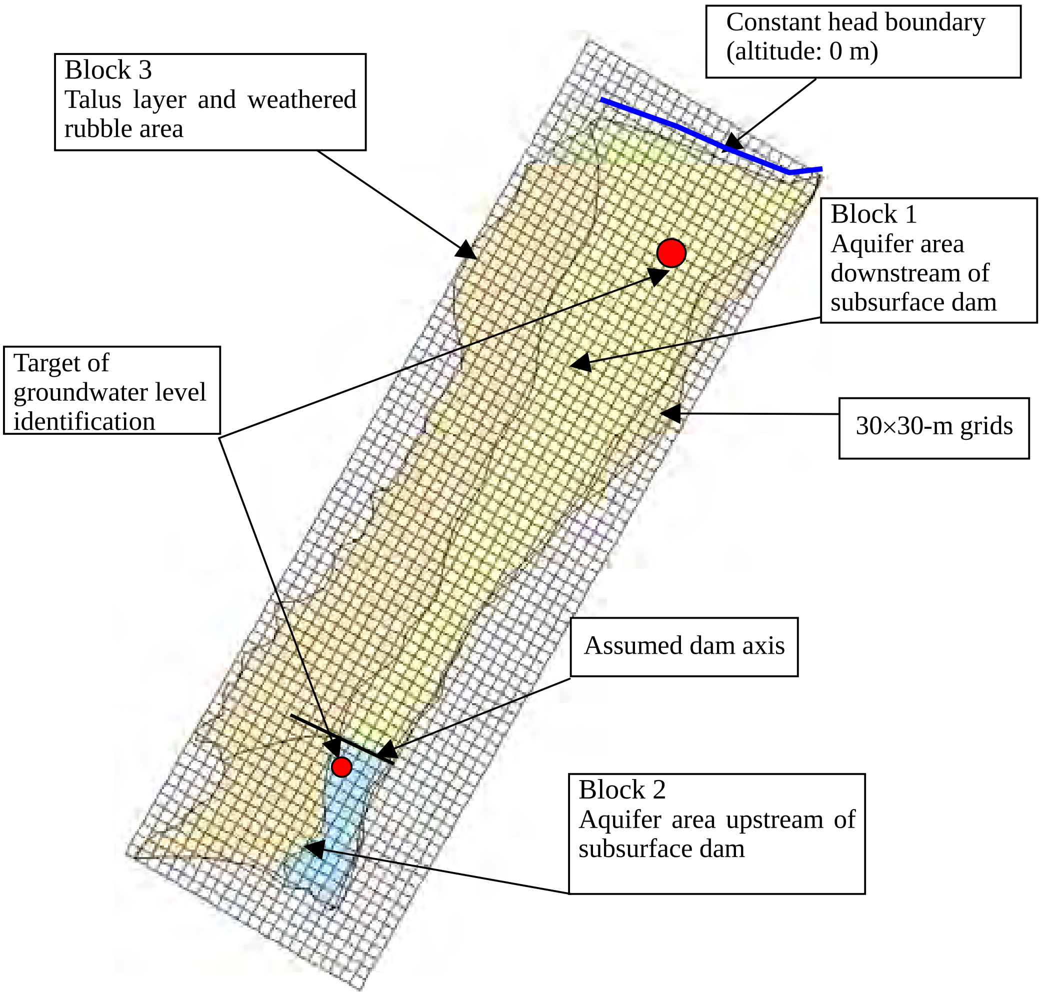
e) Calculation conditions

Calculation period: One year (from April 1, 2001 to March 31, 2002)

Calculation steps: Daily (365 steps)

Initial water level: While the analytical parameters were being adjusted, the water level was calculated experimentally. When the initial and final water levels matched, the final water level was regarded as the initial water level.

Figure 4.3.18 Diagram of Calculation Grid Division



(d) Verification

The observed groundwater levels were compared with the values calculated using the model (Figure 4.3.19). Table 4.3.7 lists the parameters used for calculation.

Figure 4.3.19 Calculated and Measured Groundwater Levels in the Aquifer Area

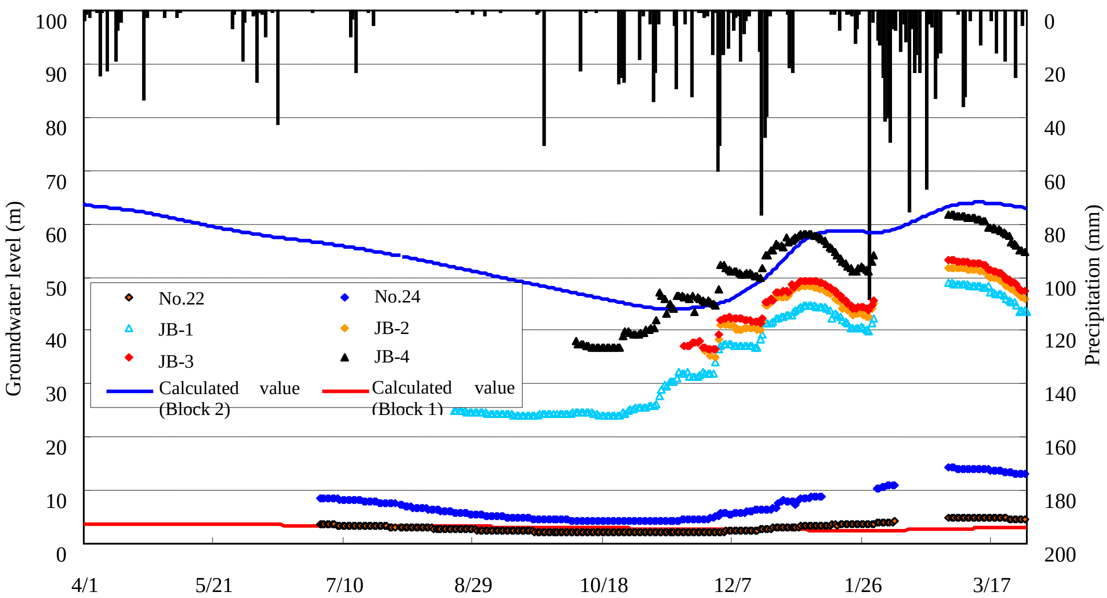


Table 4.3.7 List of Parameters

Item		Parameter Value		
		Block 1	Block 2	Block 3
Layer 1	Saturated hydraulic conductivity	17.28 m/d (1.0×10^{-2} cm/s)	21.6 m/d (3.4×10^{-2} cm/s)	0.0864 m/d (1.0×10^{-4} cm/s)
	Specific storage coefficient	0.001	0.001	0.001
	Effective porosity	0.1	0.1	0.1
Layer 2	Saturated hydraulic conductivity	17.28 m/d (1.0×10^{-2} cm/s)	21.6 m/d (3.4×10^{-2} cm/s)	0.0864 m/d (1.0×10^{-4} cm/s)
	Specific storage coefficient	0.001	0.001	0.001
	Effective porosity	0.1	0.1	0.1
Layer 3	Saturated hydraulic conductivity	0.0864 m/d (1.0×10^{-4} cm/s)		
	Specific storage coefficient	0.001		
	Effective porosity	0.1		
Altitude of drainage canal in Layer 1 aquifer area		Layer 1 surface altitude		
Coefficient of water conveyance of Layer 1 drainage canal		0.01 (Block 1, downstream side of the dam axis), 0.05 (Block 2, upstream side of the dam axis)		

(3) Forecast calculation

Using the above groundwater flow model (three-dimensional difference model), forecast water circulation when the subsurface dam is constructed.

(a) Calculation flow

1) Calculate the groundwater level fluctuation of the subsurface dam reservoir area when the permeability is set low for the assumed cut-off wall construction site. Set the hydraulic conductivity to 10^{-4}, 10^{-5}, and 10^{-6} cm/sec.
2) Calculate the exploitable quantity of water from the subsurface dam reservoir area by assuming the continuous intake of a certain quantity with no break throughout the year.

(b) Subsurface dam setting

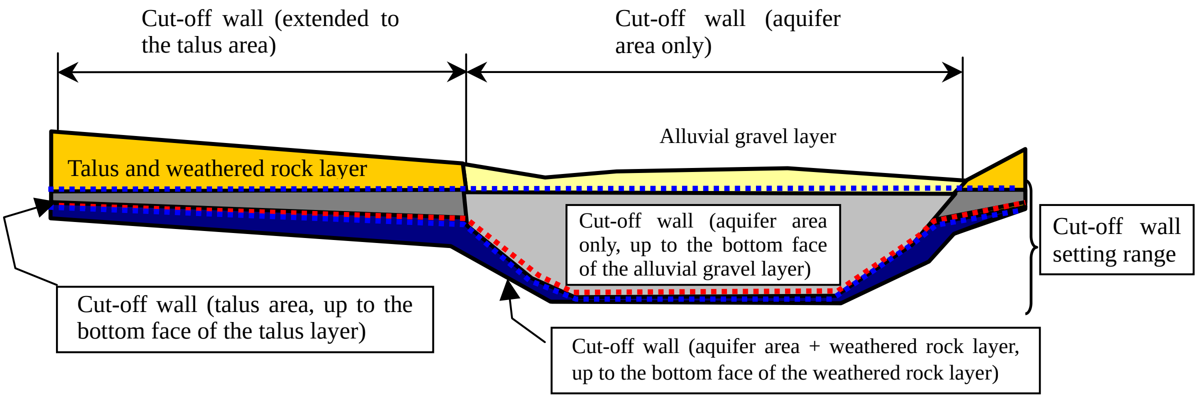
Based on the created groundwater flow model, construct a subsurface dam (cut-off wall) about 1 m thick on the assumed subsurface dam axis. Using a layer with 5×10^{-5} cm/sec in hydraulic conductivity as the basement, its upper layer is assumed as being replaced with a material of low saturated hydraulic conductivity. Considering that the design hydraulic conductivity differs depending on the method, the hydraulic conductivity of the subsurface dam was set to 1.0×10^{-4}, 1.0×10^{-5}, and 1.0×10^{-6} cm/sec.

By changing the cut-off wall installation range or the extension and depth of the cut-off wall, influences on the water environment were evaluated. The effects of cut-off wall positioning were studied with particular attention given to geology of about 10^{-4} cm/sec in hydraulic conductivity. With the above in mind, the parameters for forecast calculation are summarized in Table 4.3.8.

Table 4.3.8 Parameters Used for Forecast Calculation

<table>
<tr><th>Item</th><th>Case of Forecast Calculation</th><th>Remarks</th></tr>
<tr><td rowspan="2">Groundwater charge</td><td>Dry year (April 1997 to March 1998)
Annual precipitation: 1,599 mm</td><td rowspan="2">Dry and wet years in the tank model calculation period (1995-2002)</td></tr>
<tr><td>Wet year (April 1998 to March 1999)
Annual precipitation: 3,253 mm</td></tr>
<tr><td rowspan="4">Hydraulic conductivity of cut-off wall</td><td>No subsurface dam</td><td rowspan="4">Cut-off wall thickness: Fixed at 1 m</td></tr>
<tr><td>1.0×10^{-4} (cm/sec)</td></tr>
<tr><td>1.0×10^{-5} (cm/sec)</td></tr>
<tr><td>1.0×10^{-6} (cm/sec)</td></tr>
<tr><td rowspan="2">Depth of cut-off wall penetration part</td><td>To the bottom face of the alluvial gravel layer</td><td>Cut-off wall in the second aquifer</td></tr>
<tr><td>To the bottom face of the weathered volcanic rock layer</td><td>Cut-off wall in the third aquifer</td></tr>
<tr><td rowspan="2">Extension of cut-off wall</td><td>Aquifer area only</td><td rowspan="2"></td></tr>
<tr><td>Aquifer area + Talus area (100 m)</td></tr>
</table>

Figure 4.3.20 Subsurface dam Setting



(c) Setting of the groundwater yield

A certain quantity of groundwater will be pumped throughout the year. The possible yield means the quantity of water that can ensure an adequate groundwater level condition at the end of the dry season. When the minimum reservoir level is at the base of the alluvial gravel layer, the groundwater yield in the reservoir area on the assumed subsurface dam site is regarded as “exploitable water quantity” if it does not fall below the minimum reservoir level at the end of the dry season.

The following relation holds true for the water balance in the subsurface dam reservoir area:
Groundwater charge = Groundwater yield + Cut-off wall overflow and leakage

For groundwater consumption, intake from a well by ordinary boring is assumed. Here, one intake well will be prepared in the direct upstream mesh on the assumed dam axis at the center of the valley.

(d) Forecast calculation (wet year)

Table 4.3.9 summarizes the conditions and patterns for forecast calculation. For each different hydraulic conductivity design, four patterns were attempted in relation to the cut-off wall construction range (only the alluvial gravel layer of high permeability for the cut-off wall with the design hydraulic conductivity of 1.0×10^{-4} cm/sec).

“Charge to the subsurface dam reservoir area” is 2,281,546 m^3 in a year. Figure 4.3.21 compares the groundwater level fluctuation when a subsurface dam of each hydraulic conductivity design is constructed under the same conditions. The groundwater level is at the intake point. For the construction range, four patterns were calculated experimentally (design hydraulic conductivity: 1.0×10^{-5} cm/sec and 1.0×10^{-6} cm/sec) but did not show great discrepancies in the end.

As Figure 4.3.22 shows, an overflow from the cut-off wall occurred continuously except during several months at the end of the dry season. This indicates that the subsurface dam cannot store rain in the rainy season because the gross reservoir capacity is too small.

Table 4.3.9 Conditions and Results of Forecast Calculation (Wet Year)

Cut-off wall saturated hydraulic conductivity (cm/sec)	Depth of cut-off wall penetration part		Cut-off wall extension range		Yield		Overflow		Total	
	Alluvial range	Weathered range	Alluvial range	Talus range	1,000 tons/ year	Tons/ day	1,000 tons/ year	Tons/ day	1,000 tons/ year	Tons/ day
1.0×10^{-6}	○	-	○	-	912	2,500	1,342	3,680	2,254	6,180
	-	○	○	-	912	2,500	1,354	3,710	2,266	6,210
	○	-	-	○	912	2,500	1,342	3,680	2,254	6,180
	-	○	-	○	912	2,500	1,355	3,710	2,267	6,210
1.0×10^{-5}	○	-	○	-	839	2,300	1,299	3,560	2,138	5,860
	-	○	○	-	839	2,300	1,299	3,560	2,138	5,860
	○	-	-	○	839	2,300	1,299	3,560	2,138	5,860
	-	○	-	○	839	2,300	1,300	3,560	2,139	5,860
1.0×10^{-4}	○	-	○	-	693	1,900	1,018	2,790	1,711	4,690
No dam	-	-	-	-	657	1,800	894	2,450	1,551	4,250

Figure 4.3.21 Forecast Calculation of Groundwater Level Fluctuation (Wet Year)

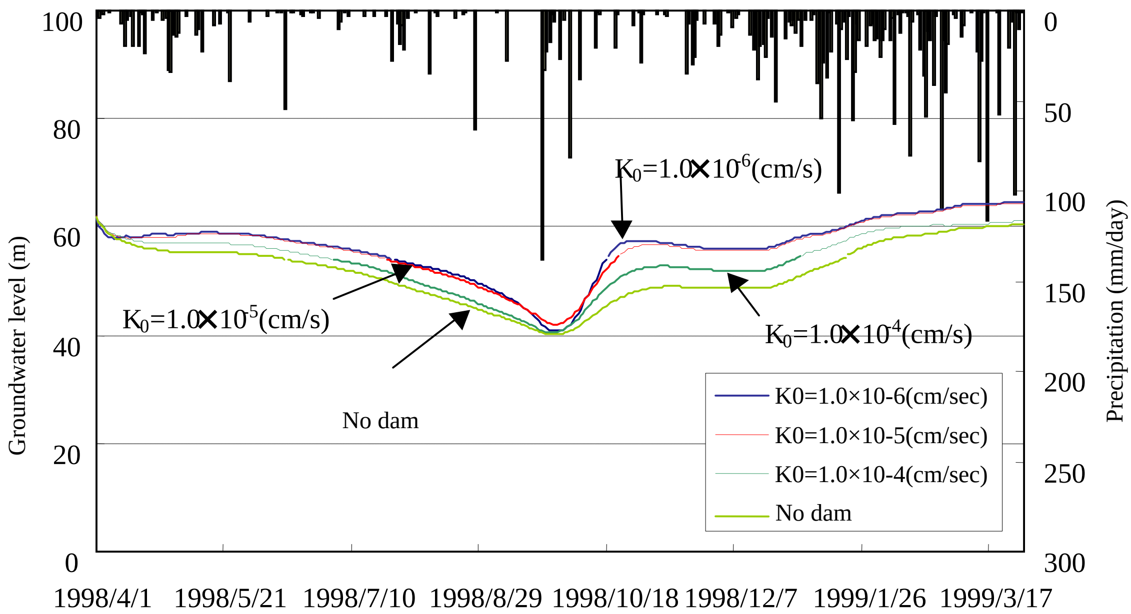
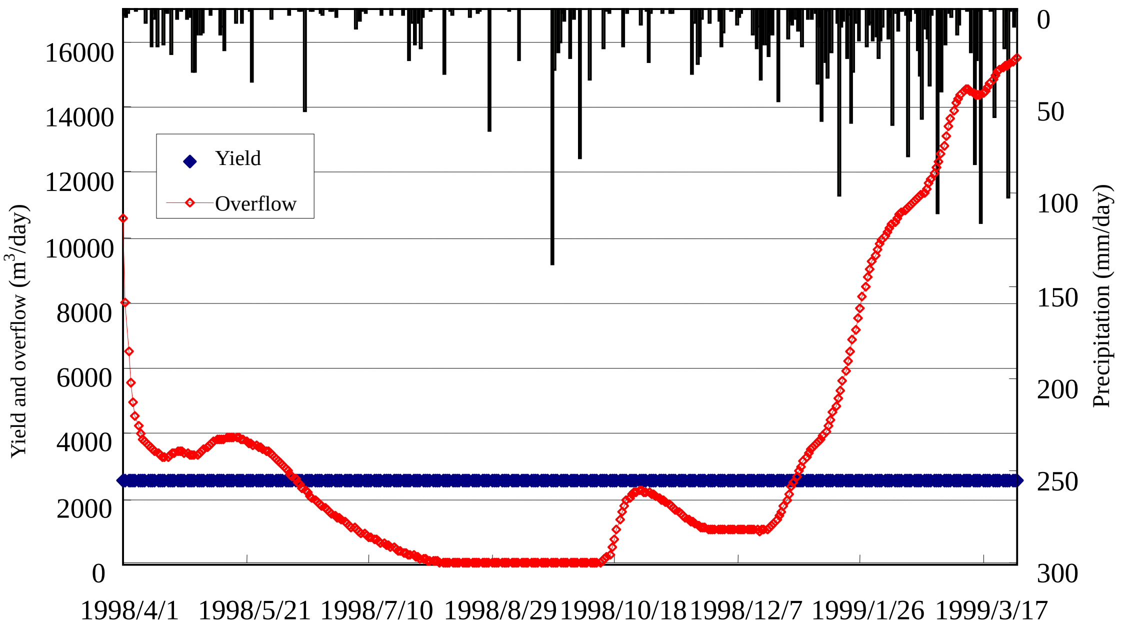


Figure 4.3.22 Daily Fluctuations of Yield and Overflow (Wet Year)



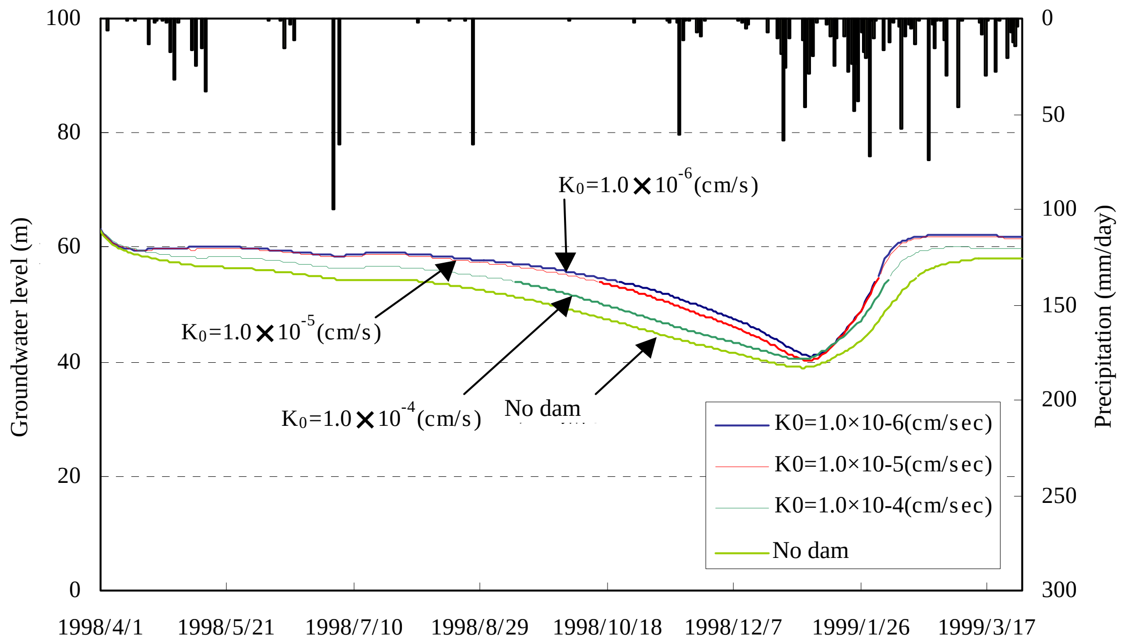
(e) Forecast calculation (dry year)

As in the wet year, Table 4.3.10 lists the conditions and patterns of forecast calculation. Figure 4.3.23 shows the groundwater level fluctuations forecast under the conditions. “Charge to the subsurface dam reservoir area” is 1,116,779m^3 in a year.

Table 4.3.10 Conditions and Results of Forecast Calculation (Dry Year)

Cut-off wall saturated hydraulic conductivity (cm/sec)	Depth of cut-off wall penetration part		Cut-off wall extension range		Yield		Overflow		Total	
	Alluvial range	Weathered range	Alluvial range	Talus range	1,000 tons/ year	Tons/ day	1,000 tons/ year	Tons/ day	1,000 tons/ year	Tons/ day
1.0×10^{-6}	○	-	○	-	438	1,200	683	1,870	1,121	3,070
	-	○	○	-	438	1,200	693	1,900	1,131	3,100
	○	-	-	○	438	1,200	684	1,870	1,122	3,070
	-	○	-	○	438	1,200	693	1,900	1,131	3,100
1.0×10^{-5}	○	-	○	-	365	1,000	646	1,770	1,011	2,770
	-	○	○	-	365	1,000	648	1,780	1,013	2,780
	○	-	-	○	365	1,000	647	1,770	1,012	2,770
	-	○	-	○	365	1,000	648	1,780	1,013	2,780
1.0×10^{-4}	○	-	○	-	182	500	464	1,270	646	1,770
No dam	-	-	-	-	146	400	346	950	492	1,350

Figure 4.3.23 Forecast Calculation of Groundwater Level Fluctuation (Dry Year)



(4) Study of the subsurface dam operation plan

(a) Idea of exploitable water quantity

The rate of ordinary water consumption varies with the season. The rate of water consumption does not increase or decrease according to rainfall or other meteorological changes but varies as scheduled on a certain level. If the necessary water quantity is constant throughout the year, the exploitable water quantity is only "Groundwater yield" in a dry year as shown in Table 4.3.10.

The forecast calculation indicates that about 300,000 to 400,000 m^3 can be exploited annually. It was also found that dead runoff of 700,000 to 800,000 m^3 cannot be avoided even in a dry year. Overflow water from the cut-off wall accounts for most of the dead runoff, which in a dry year will be about 1,800,000 to 1,900,000 m^3. As Figure 4.3.22 shows, the overflow continues with no break in the rainy season and fluctuates greatly. It is difficult to capture and use this irregular overflow water.

Dead runoff increases because the subsurface dam capacity is too small and the charge to the small subsurface dam reservoir area is unstable in the rainy season.

(b) Water source management and operation

The project objective of a subsurface dam in Ketes is to store water welling up and flowing underground from an upstream area. However, the subsurface dam can capture only less than half the water and most water in the rainy season overflows the subsurface dam to the downstream as dead runoff.

Considering this, constructing a diversion weir directly downstream of the springs to take a certain quantity of surface water before it flows underground may be a means of reducing dead runoff. This is to store only water not captured by the diversion weir in the subsurface dam. As Figure 4.3.24 shows, about 500 m^3/day of water can be exploited even where the water quantity is at the minimum for the year.

For the irrigation of produce such as paddy rice and maize, overflow water in the rainy season from December to April can be used effectively. In Ketes, the local water resources can probably be used more effectively by surface water exploitation as well as subsurface dam construction.

Figure 4.3.24 Spring Water Utilization Plan

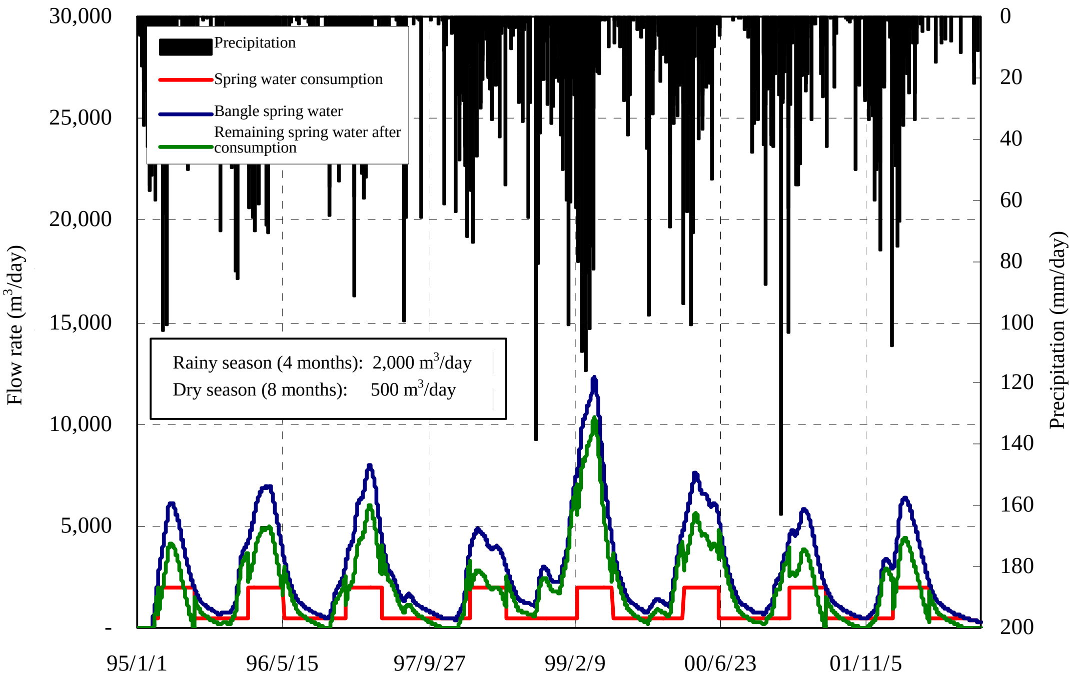


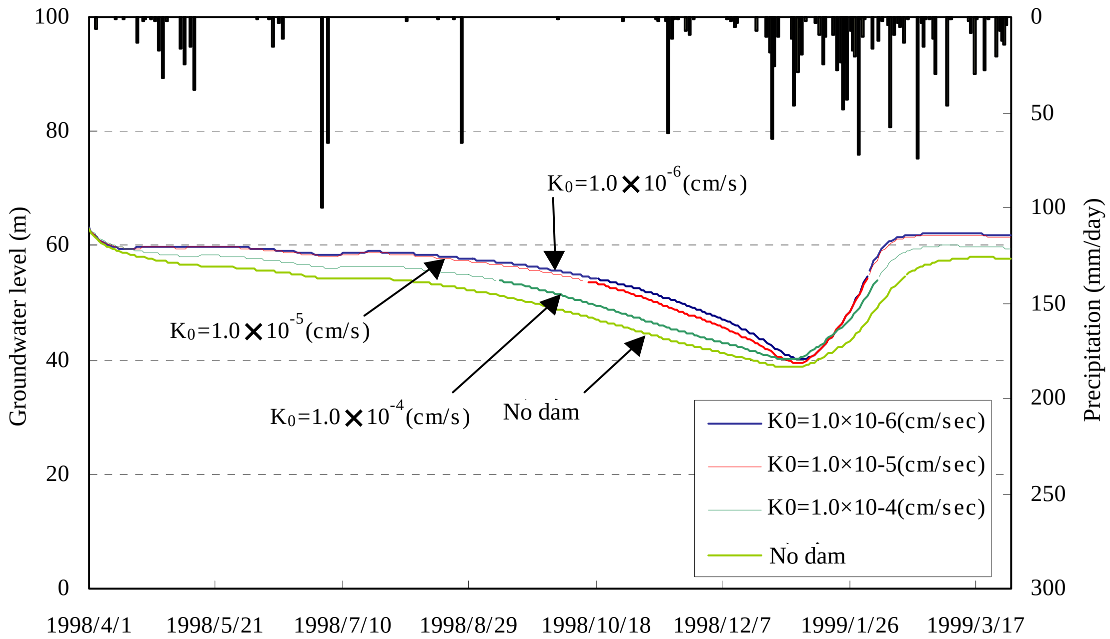
Figure 4.3.25 shows the fluctuation of the groundwater level in the subsurface dam reservoir area when the spring water consumption is merely added to the exploitable water quantity. For the forecast calculation, the groundwater flow model (three-dimensional difference model) previously constructed is used.

Charge to the subsurface dam reservoir area is calculated using the series tank model. This is basically equal to the surface water at the boundary between Blocks 6 and 5 (Figure 4.3.7) after the specified quantity in Figure 4.3.24 is subtracted. Table 4.3.11 lists the calculation conditions.

Table 4.3.11 Conditions and Results of Forecast Calculation

Cut-off wall saturated hydraulic conductivity (cm/sec)	Depth of cut-off wall penetration part		Cut-off wall extension range		Yield		Overflow	
	Alluvial range	Weathered range	Alluvial range	Talus range	1,000 tons/year	Tons/ day	1,000 tons/year	Tons/ day
1.0×10^{-6}	○	-	○	-	438	1,200	660	1,808
	-	○	○	-	438	1,200	671	1,838
	○	-	-	○	438	1,200	662	1,814
	-	○	-	○	438	1,200	672	1,841
1.0×10^{-5}	○	-	○	-	365	1,000	624	1,710
	-	○	○	-	365	1,000	625	1,712
	○	-	-	○	365	1,000	624	1,710
	-	○	-	○	365	1,000	624	1,710
1.0×10^{-4}	○	-	○	-	182	500	447	1,225
No dam	-	-	-	-	146	400	334	915

Figure 4.3.25 Forecast Calculation of Groundwater Level Fluctuation (Dry Year)



Farmland areas that can be covered by the above exploitable water sources were approximately calculated. The subsurface dam can cover fields of 30 to 40 ha and the upstream diversion weir can cover fields of 20 ha throughout the year and 60 to 70 ha (paddies of 7 ha) in the rainy season. Therefore, if the subsurface dam and upstream diversion weir are combined, water can be supplied to fields of 50 ha throughout the year.

Table 4.3.12 Approximate Exploitable Water Quantity

Water Source	Throughout the Year (A)		Increase in the Rainy Season (B)		Irrigation in the Rainy Season (A+B)	
	Quantity	Area	Quantity	Area	Quantity	Area
Diversion weir	500 m^3/day	17 ha (2 ha)	1,500 m^3/day	50 ha (5 ha)	2,000 m^3/day	67 ha (7 ha)
Subsurface dam	1,000 m^3/day	33 ha	0 m^3/day	0 ha	1,000 m^3/day	33 ha
Total	1,500 m^3/day	50 ha	1,500 m^3/day	50 ha	3,000 m^3/day	100 ha

4.3.6 Feasibility of subsurface dam development

(1) Relationship between subsurface dam dimensions and exploitable quantity

According to the forecast calculation, the exploitable quantity will not change greatly even if the geology assumed to be about 1.0×10^{-4} cm/sec in hydraulic conductivity (talus layer and volcanic rock weathered layer) is replaced with a cut-off wall of 1.0×10^{-5} or 1.0×10^{-6} cm/sec. This means that installing a cut-off wall at alluvium will be adequate if only the permeability of geology is uniform. The construction will be about 150 m in total length and 30 m in maximum depth.

The design hydraulic conductivity of the cut-off wall greatly affects the exploitable quantity. In particular, the difference between 1.0×10^{-4} cm/sec and 1.0×10^{-5} cm/sec is very influential. This indicates that hydraulic conductivity of about 1.0×10^{-5} cm/sec is preferable for subsurface dam construction.

(2) Dimensions of the assumed subsurface dam

In this region, the geology of the lowest permeability is composed of hard volcanic rocks at the bottom of the three-layer structure (Figure 4.3.5). The target hydraulic conductivity is about 5×10^{-5} cm/sec. This will be the hydraulic basement for subsurface dam construction.

Construction of the cut-off wall involves processing high-permeability alluvium (riverbed sediments) and volcanic rocks or replacing them with materials of low permeability to impede the permeation of water. Whichever method is adopted, the target permeability will be about 5×10^{-5} cm/sec or more, which is about the same as hard volcanic rocks or more.

The following two kinds of methods can be assumed:

1. Shallow (depth: 15 m or less): Open excavation and replacement-backfilling
   Deep: Grouting
2. Trench excavation and self-hardening slurry replacement

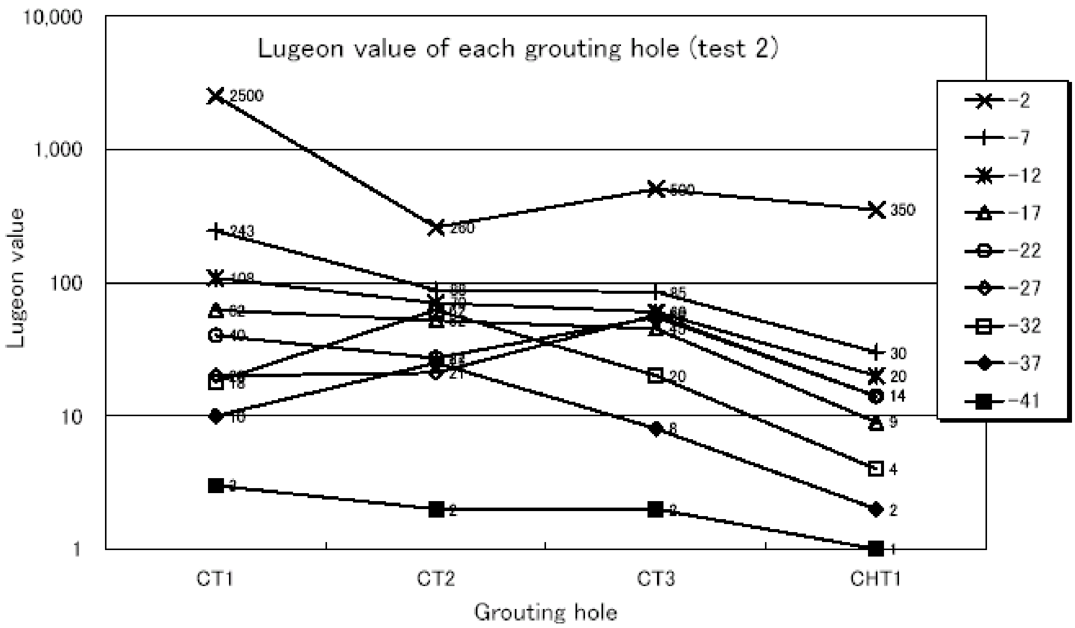
For secure cut-off, the latter method is advantageous because it is generally used to improve the basement for high-rise building construction and its processes are not complicated.

From the results of the boring survey, it is known that the former method will require a grouting section of at least 150 m. Grouting usually manifests its effectiveness when two or three arrays of grouting holes with 2-m intervals are drilled. More than 150 grouting holes will be necessary. Furthermore, it may not be possible to achieve cut-off performance as designed where riverbed sediments having hydraulic conductivity of 10^{-2} cm/sec order may not be secured. This is not a low-cost method and there are many indefinite factors regarding the cut-off performance.

The Water Resources Research Center of Indonesia previously conducted a grouting test on this site. Boreholes arranged in the form of a regular triangle (interval: 3 m) were sequentially filled with ordinary Portland cement and the final effects of improvement were evaluated at the check hole located at the gravity center of the triangle. The test was conducted at two stages, up to 15 m deep and up to 40 deep, and reveals the following:

1. The filled cement quantity and Lugeon value are smaller for a later hole. In particular, the check hole showed obvious effects of grouting. As the depth increases, the injection pressure rises.
2. The permeability was improved from 250–40 Lu at the upper part of the alluvium and 20–40 Lu at the lower part to 10–30 Lu at the check hole, and from 10–20 Lu at the surface weathered section of the basement and 1–3 Lu at the hard section to about 2 Lu at the check hole. In other words, grouting can be expected to reduce the hydraulic conductivity in the order of 1 or 2.

Figure 4.3.26 Lugeon Fluctuation by Grouting
(40-m test hole)



Permeability was improved to 20–50 Lu, nearly equal to the saturated hydraulic conductivity of 1.0×10^{-4} cm/sec at 5 m or deeper, but to 2–5 Lu at 30 m or deeper in the volcanic rock layer. For secure cut-off performance, permeability of about 2–5 Lu is preferred. Whether or not the alluvium can be so improved by grouting is a subject for future study.

The dimensions of the assumed subsurface dam are summarized below.

- Total length of the subsurface dam cut-off wall: 150 m min
- Maximum depth of the subsurface dam cut-off wall: About 35 m
- Reservoir capacity: 50,000 to 100,000 m^3
- Design hydraulic conductivity of the dam: 5×10^{-5} cm/sec or more

(3) Exploitability of other water sources

The exploitability of water sources other than the subsurface dam is discussed here.

(a) Surface water

As mentioned in the previous section, the surface water near the Bangle springs (upstream of the assumed subsurface dam reservoir area) is a practical water source. Since a diversion weir does not have a storage function, compensation with a farm pond or other reservoir facilities may be worth studying.

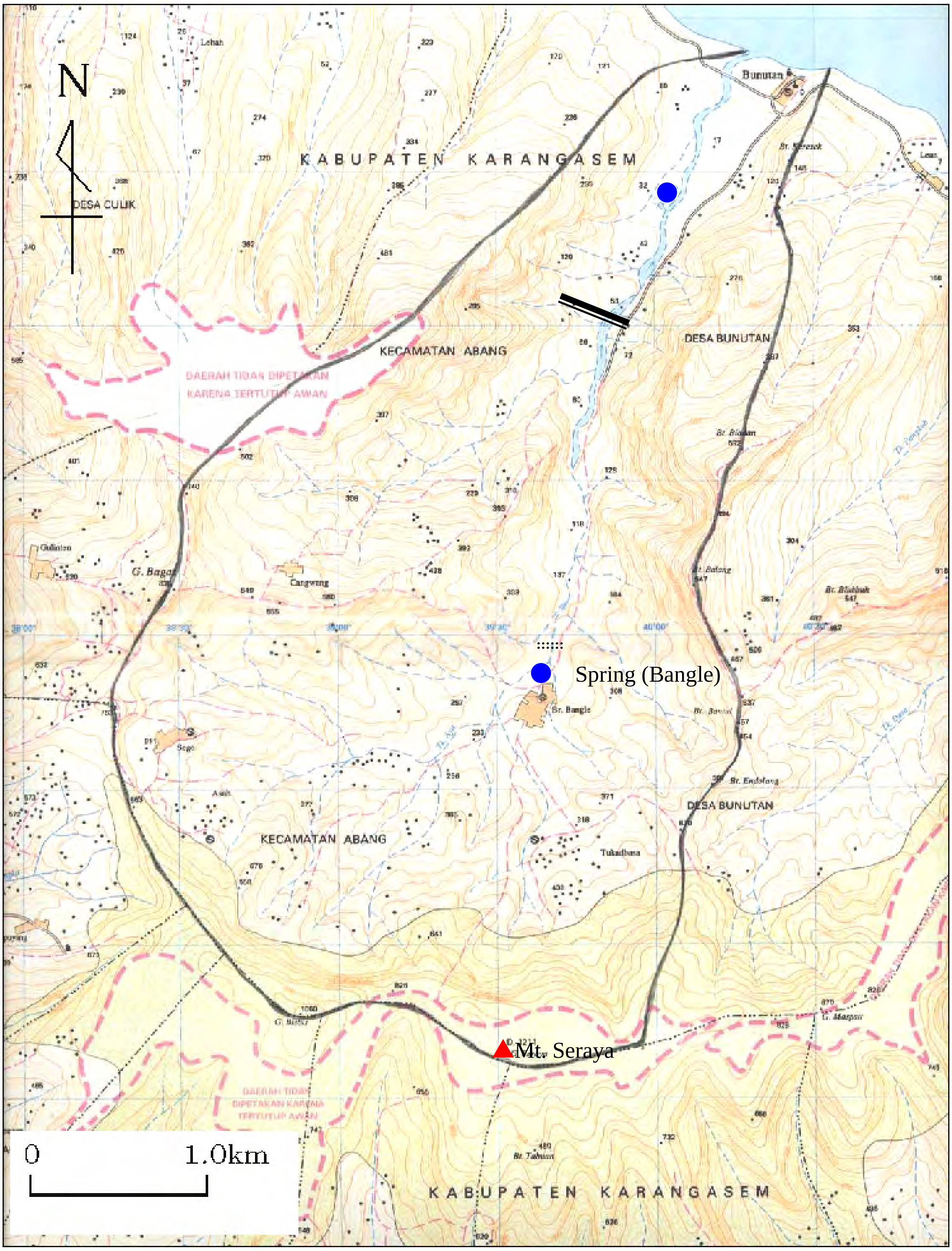
A surface dam will guarantee an accurate and stable water supply. Needless to say, however, the dam construction will be expensive and the reservoir will significantly limit and impose sacrifices on living conditions, land use, and ecosystem. We should also note that sedimentation (earth deposition), wear and aging of cut-off wall facilities, and many other elements will be obstacles to future continuous development.

(b) Ordinary groundwater

On the assumed subsurface dam site, the groundwater level is up to about 30 m below the surface at the end of the dry season. In the downstream area, however, the annual fluctuation of groundwater level becomes small. In this area, deep-layer groundwater may also be highly exploitable. Consumption not beyond charge will allow continuous use. From the aforementioned forecast calculation, the daily mean overflow is estimated to be over 1,500 m^3 even when the subsurface dam is constructed. A rather remarkable quantity of water from this overflow may be exploitable.

Based on the above, the water resource exploitation methods are summarized in Figure 4.3.27.

Figure 4.3.27 Location Map of Potential Water Resources



Legend
== Diversion weir
● Drilling well
▬ Subsurface dam

(4) Study of farm village improvement plan

(a) Agriculture and land status

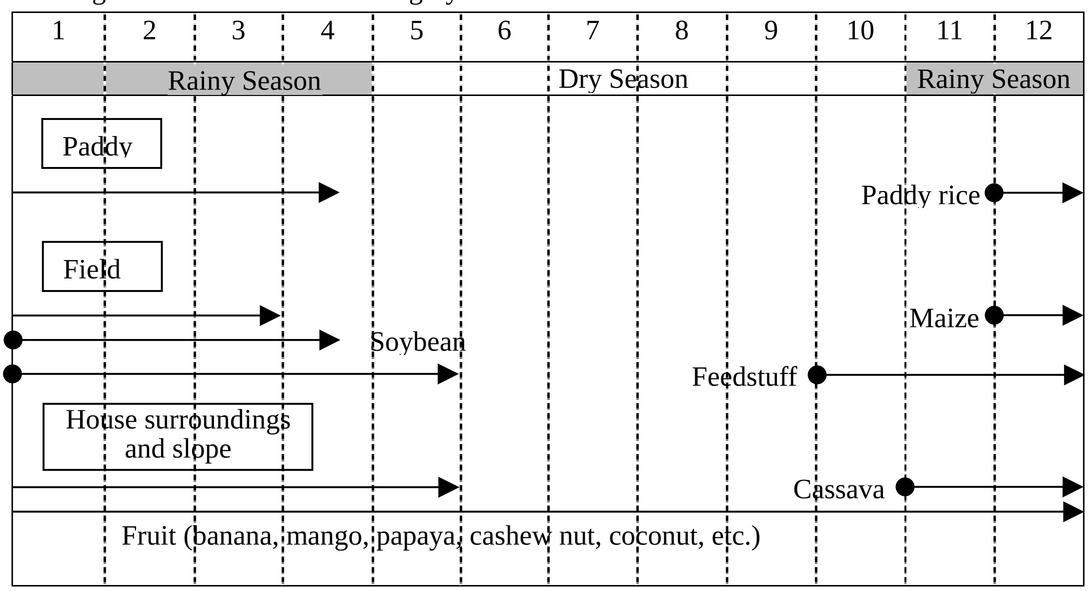
About 800 households or 3,800 people live in the catchment area of the Ketes River and about 40% of the catchment area (1,400 of 3,800 ha) is used as farmland. The residents make their living in various primary industries, such as farming, livestock breeding, and fishing. The average farming household is small with a family of 5 or 6 members and 0.7 ha of farmland (excluding orchid fields and pastures). The livestock consists of not more than three or four cattle, one sheep, one or two pigs, and six fowl.

In the dry season, the residents give up farming because of water shortage and go fishing in handmade boats to compensate for the family budget. Basically, agricultural produce is for self-supply and livestock, fruit (bananas, cashew nuts, etc.), and fish are for cash income.

Only about 100 ha of land are of a comparatively gentle inclination, such as the flood plains in the downstream area of the Ketes River. Most of the farmland is terraced from the steep slopes on both banks of the Ketes River. The major part of the paddy field area is directly downstream from the Bangle springs at the midstream and not more than 30 ha is used for the production of rice in the rainy season only. On the narrow terraced farmland, not only field produce but also orchids, pasture, and feed beans are cultivated, but productivity is extremely low.

Cassava is produced using the single cropping method and maize and beans are produced using mixed and alternate cropping. The produce from permanent cropping is fruit, such as banana, mango, papaya, cashew nut, and coconut. Maize, cassava, and beans, which are mostly self-supplied as staples, are produced in the rainy season only.

Figure 4.3.28 Current Planting System



(b) Current water use

In addition to an organization for repairing and managing farming facilities, this region has an organization for managing irrigation water. The water source is the Bangle springs only, which is basically used free of charge. For the downstream community, however, a company supplies water for drinking and miscellaneous use to public facilities (doubling as baths) through vinyl chloride piping.

Many of the residents in the downstream community go to one of the seven public places to draw water. One family uses about 30 liters a day for drinking. They also wash clothes and take baths at the public places.

Water for farming depends on rain, except for the paddy fields in the middle catchment area.

(c) Farmers' expectations

The local residents (farmers) expect to use a stable water source for the following:

- Creating new paddy fields
- Cultivating rice, soybean, vegetables, and fruit in the dry season
- Cultivating shallots and cashew nuts for cash
- Producing more feedstuff to increase number of cattle
- Cultivating soil-preserving produce to prevent soil erosion or drought from deteriorating the soil
- Supplying more water to the downstream community, hotels and other sightseeing facilities for drinking and miscellaneous use

Sightseeing is the most practical and effective measures of local promotion for this region. Serving local foods at hotels will be beneficial for general promotion, and the price of agricultural produce will not be dominated by the market. If sightseeing is promoted, the local residents will be more motivated.

(d) Basic development plan of the farm village

The basic idea of agricultural promotion is as follows:

1) Maintaining and managing the irrigation facilities

Create a planting plan mainly among the farmers (residents). Based on this plan, roughly determine an annual pattern of water use and study a distribution plan. For efficient and democratic operation, maintenance, and management of irrigation facilities, establish a new water management union or reform an existing organization.

2) Maintaining the ground power and stabilizing crops

Study such measures as the prevention of soil erosion to minimize the nutrition discharge, the adjustment of land use to avoid biased nutrition intake, and the reduction of organic soils to maintain land productivity.

The measures for preventing soil erosion include contour cultivation represented by terrace paddy fields, agro-forestry for tree planting and produce cultivation, mulching for covering the soil surface with produce stalks and leaves or weeds, and masonry work.

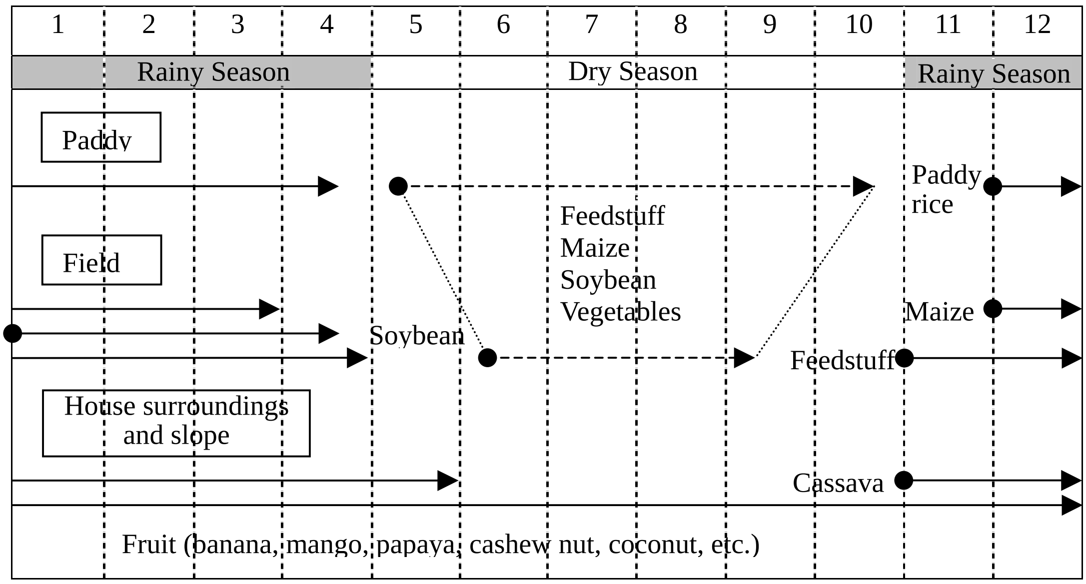
The measures for adjusting the land use are mixed, mutual, or rotational cropping with beans and agro-forestry.

The means for preventing degradation of organic soils is to administer livestock dung, compost, or fish powder.

3) Reviewing the farmer support system

While considering measures for maintaining the ground power, introduce as many kinds of produce as possible, including produce for cash, to improve the efficiency of land use. Establish an agricultural production union to support the farmers' efforts and promote local integrated efforts. Technical guidance by instructors is necessary for improving the agricultural production technology. Figure 4.3.29 shows an example of a planting improvement plan.

Figure 4.3.29 Planting Improvement Plan



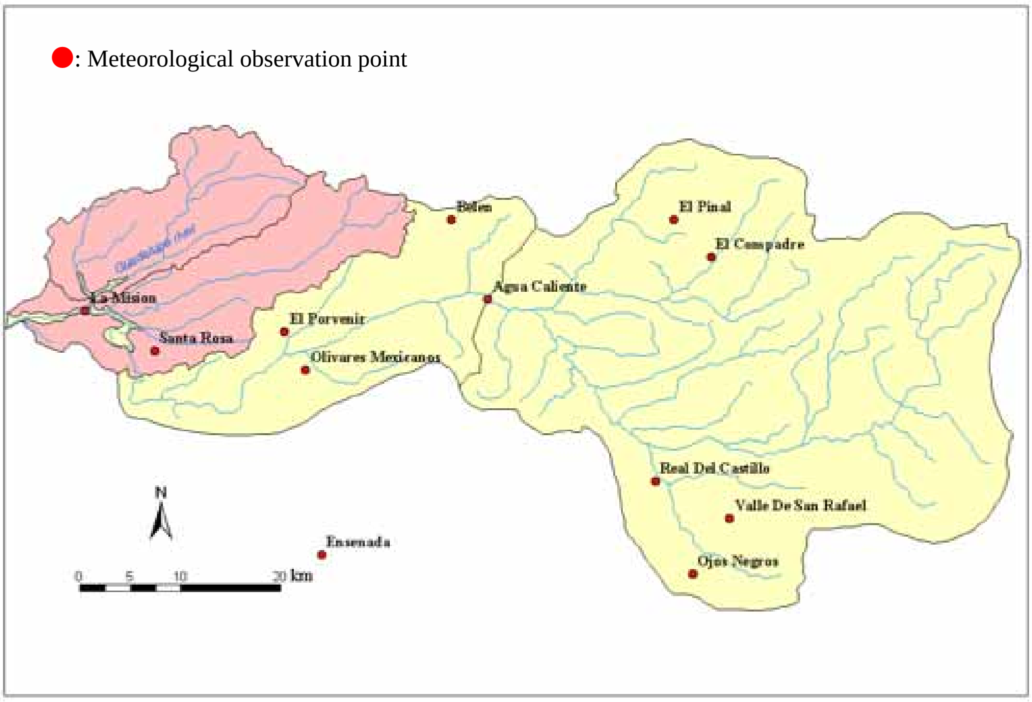
4.4 Case Survey: La Mision, Mexico

4.4.1 Selection of survey area

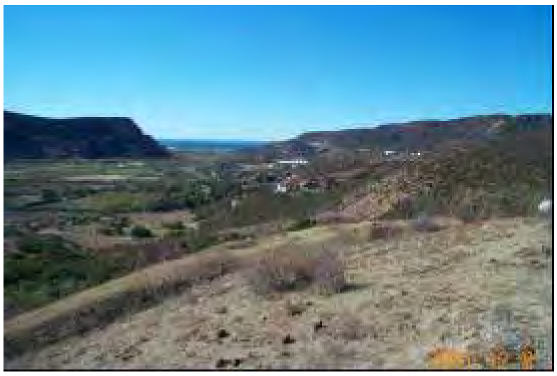
From the three candidate sites for subsurface dam construction selected by the preliminary survey, La Mision was chosen for the following reasons:

- Groundwater is popularly used for irrigation and drinking and excess pumping may result in groundwater salinization.
- The underground valley in the downstream catchment area is comparatively narrow and suitable for cut-off; the upstream side of the cut-off may become an influential reservoir pocket for groundwater.
- There is a large amount of existing survey material on the geology and groundwater of the area to enable an efficient survey.

Figure 4.4.1 Guadalupe River Catchment Area and Meteorological Observation Points



La Mision downstream catchment area from the left bank



Panoramic view of La Mision downstream catchment area

4.4.2 Outline of the survey area

La Mision is located on the northern end of the California Peninsula and consists of a ravine plain (facing the Pacific Ocean) and its surrounding plateaus. The Guadalupe River flowing down through the center of this region originates from the cordillera of the California Peninsula. This river, which flows into the Pacific Ocean, is 115 km long and its catchment area is about 2,500 km^2. This region is located at the downstream end.

(1) Meteorology

The annual mean precipitation is about 300 to 400 mm. The precipitation fluctuates greatly and may even exceed 500 m, much greater than the annual mean, every several years. By month, the precipitation tends to be high in October to April and low in May to September. From June to August, almost no precipitation is observed.

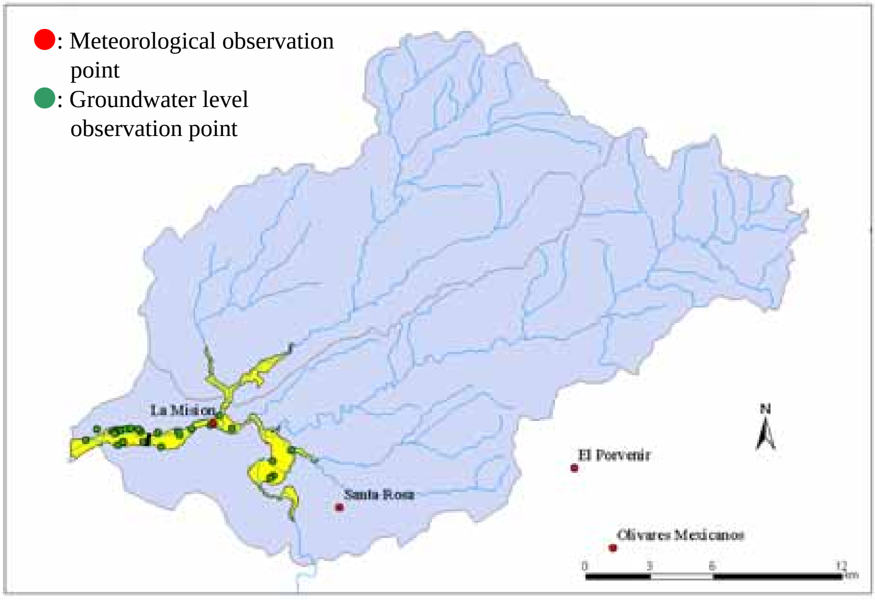
Under the influence of cold currents in the Pacific Ocean, the temperature in this region located at lat. 32° N rises only to about 20°C even in summer and falls to about 10°C in winter. In sharp contrast, the temperature reaches about 40°C in an area located at the same latitude along the California Bay about 100 km to the east.

(2) Topology and geology

The surroundings are plateaus 200 to 300 m in altitude. La Mision is a dissected valley formed by the Guadalupe River, and the 100-m-wide ravine plain can be tracked about 9 km to the north or south. Earth carried by the Guadalupe River is deposited in the ravine plain.

At the boundary between the plateaus and the ravine plain, terraced or steep slopes are formed. The plateaus are mainly composed of basalt, but siltstones of the Cretaceous Period to the Tertiary Period are exposed at the foot of the slopes.

Figure 4.4.2 Location Map of the Survey Area



(3) Water environment

The riverbed sediments composing the ravine plain are a major aquifer. The Guadalupe River is dry except when rain falls heavily in the catchment area once every several years. The groundwater level is less than several meters below the surface and the groundwater surfaces at concave areas on sand-dug sites spattered along the river. Leaving these sand-dug sites is not favorable for using or preserving groundwater because of potential groundwater contamination or evaporation.

Because of abundant groundwater, there are many wells in the ravine plain and a large amount of groundwater is used. The groundwater is used for many purposes but a significant yield is for tap water and supplied to nearby cities through pipelines. The groundwater within 2 km from the coast is remarkably salinized.

The valley is narrowed at some places. This topography is convenient for cut-off by a subsurface dam.

4.4.3 Topographical and geological surveys

(1) Topographical survey

The existing topographical maps are of [1:25,000] scale covering the entire catchment area and [1:5,000] scale covering the downstream riverbed of the Guadalupe River. The latter expresses the riverbed landform in detail.

(2) Electric prospecting

Figure 4.4.3 shows the range of electric prospecting. This is located at a narrow part of the valley, a candidate site for subsurface dam construction.

Figure 4.4.3 Geological Map of La Mision

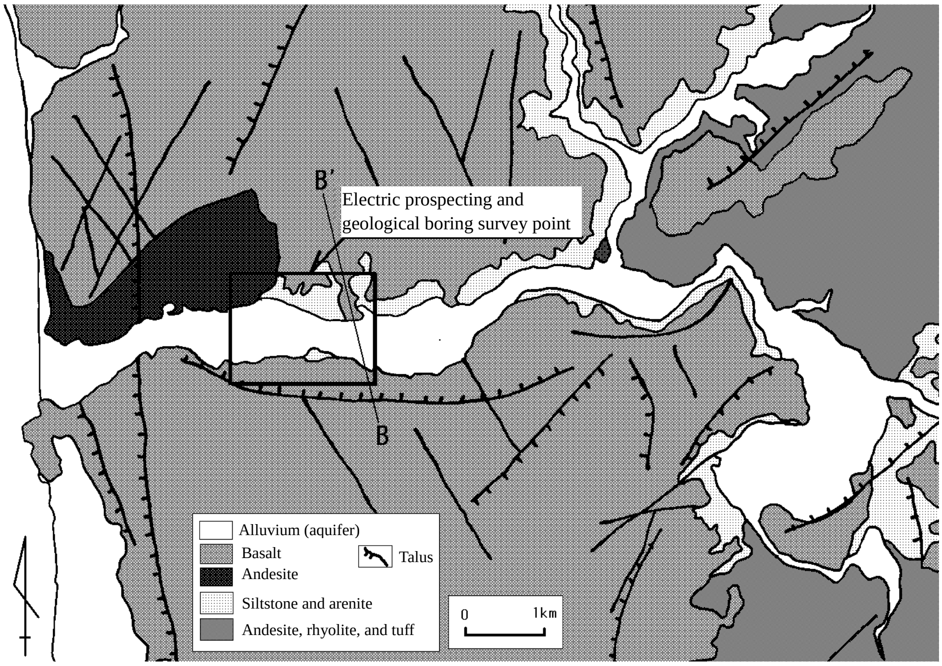


Table 4.4.1 gives the assumed geologic stratigraphy of this region. The purpose of electric prospecting is to check the geological depth distribution. Siltstones of the Cretaceous Period can be expected as the hydraulic basement.

Table 4.4.1 Geologic Stratigraphy of La Mision

Era	Stratum and Rock	Permeability	Hydraulic Properties
Quaternary Period	Alluvium (sand, gravel, silt)	High	Aquifer
	Basalt	Medium	
Tertiary Period Miocene - Cretaceous Period (Latter)	Andesite	Medium	
	Siltstone, arenite	Low	Basement
Cretaceous Period (Former)	Volcanic rocks (andesite, etc.)	Low	Basement

For electric prospecting, vertical electric sounding using the resistivity method was performed at 61 points on five survey lines perpendicular to the valley of La Mision and on two lines parallel with the valley on the left bank. The electrodes were arranged using the Schlumberger method.

Figure 4.4.4 Location Map for Electric Prospecting and Geological Boring Survey

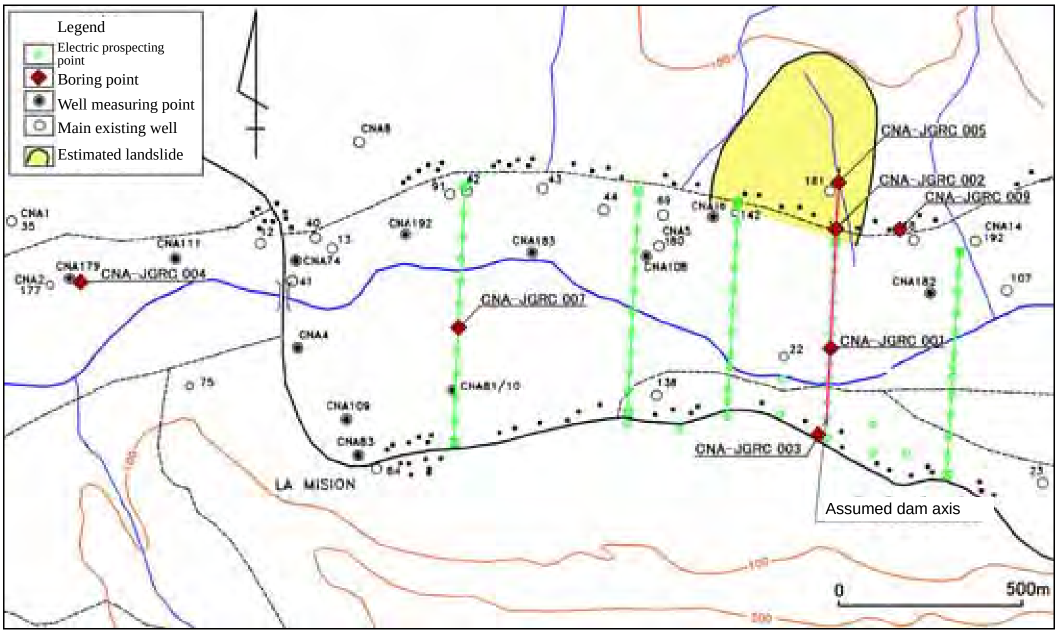


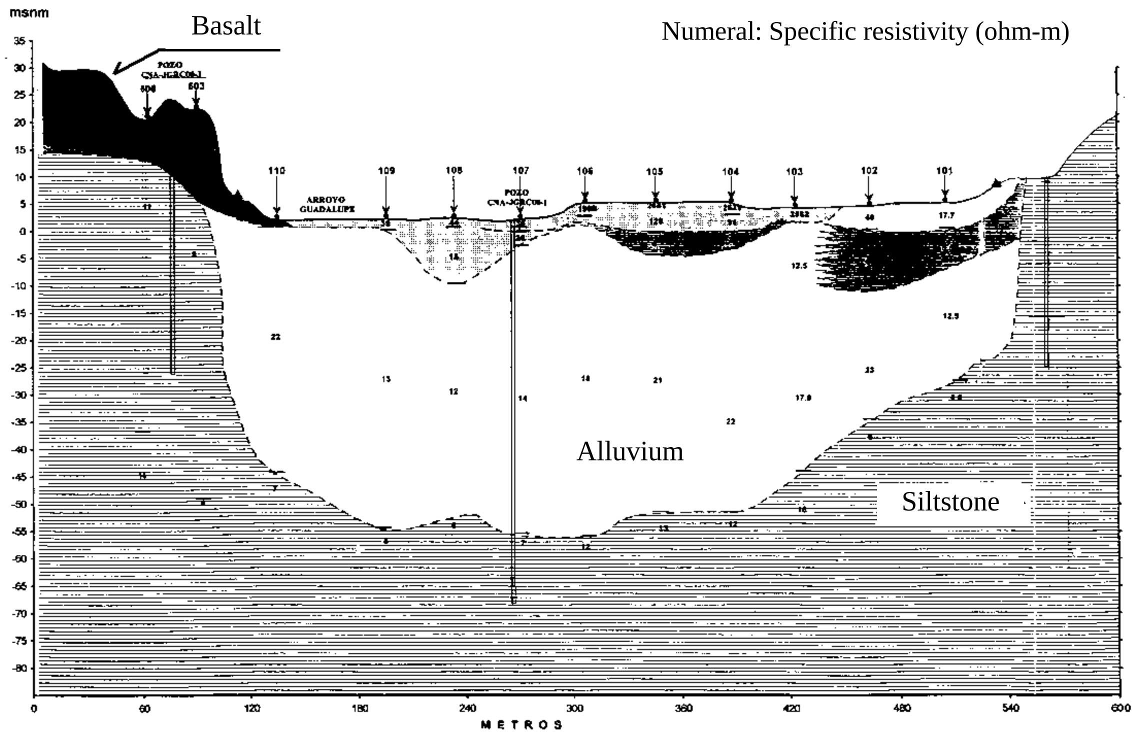
Table 4.4.2 compares the electric prospecting results and the assumed geologic resistivity. The siltstones composing the basement of the underground valley have the lowest resistivity of 2 to 15 ohm-m. The alluvium resistivity is in the range from 8 to 33 ohm-m, which is low for a stratum of mainly sand. This is probably due to the high electric conductivity of the groundwater, resulting in low stratum resistivity measurement. Resistivity of the slope sediments and alluvium varies greatly but is relatively higher than that of the lower siltstones.

Table 4.4.2 Soil and Resistivity

Soil	Dispersion Range	Resistivity (ohm-m)
Slope sediments (basalt, etc.)	Left bank	12 – 190
Alluvium (surface)	Riverbed surface	Varying greatly but relatively high
Alluvium	Inside underground valley	8 – 33
Siltstone	Right and left banks, underground valley basement	2 – 15

Figure 4.4.5 shows a cross-sectional image of resistivity. The geological depth distribution estimated from the results of electric prospecting does not precisely match that verified by past boring surveys. This is probably attributable to the fact that groundwater salinization reduced the resistivity of the alluvium of substantially high resistivity, and obscured the difference from the basement of siltstones. However, the rough tendency of stratigraphy could be grasped.

Figure 4.4.5 Cross-sectional Image of Resistivity Based on the Results of Electric Prospecting (Assumed Dam Axis)



(3) Boring survey

Boring surveys were conducted at eight points in total (see Figure 4.4.4 for the points). See Table 4.4.3 for the contents of surveys.

(a) Excavation

For aquifer evaluation, continuous core observation and core soil testing is important. However, the core collection rate was generally low presumably because the unconsolidated silt, sand, and gravels composing the alluvium were flung away by water at excavation. It seemed necessary to improve the core collection rate by introducing core pack tubing.

After excavation, a perforated vinyl chloride pipe was inserted to finish the hole for observation of the groundwater level and water quality. By leveling, the ground altitude at the boring point and the altitude at the pipe-head observation reference point were measured.

Table 4.4.3 Boring Surveys

Hole Name	Purpose of Survey	Location	Point (Latitude/Longitude)	Ground Altitude (EL.m)	Top Altitude of Hole Protection Block (EL.m)	Hole Altitude (Observation Hole Reference Point) (EL.m)	Depth (GL-m)	Excavation Diameter (cm)	Casing Diameter (cm)	Contents of Survey
CAN-JGRC 001	Cut-off center survey Reservoir survey	Dam axis center	32° 05´42.736″N 116° 50´42.556″W	2.703	3.222	3.696	70.0	9.01	5.08	All-core Field permeability test
CAN-JGRC 002	Cut-off right bank survey	Dam axis right bank	32° 05´57.194″N 116° 50´41.491″W	9.537	10.082	10.476	34.0	9.01	5.08	All-core Field permeability test
CAN-JGRC 003	Cut-off left bank survey	Dam axis left bank	32° 05´31.943″N 116° 50´42.972″W	25.956		26.466	51.0	9.01	5.08	All-core Field permeability test
CAN-JGRC 004	Installation of groundwater continuous observation hole in downstream area	Downstream area	32° 05´52.334″N 116° 52´06.588″W	1.705		2.586	20.0	9.01	5.08	Non-core Installation of self-recording observation gages (WL, EC, pH, T)
CAN-JGRC 005	Cut-off right bank survey	Abut on dam axis right bank	32° 05´59.132″N 116° 50´38.936″W	27.521	28.026	28.235	33.5	9.01	5.08	All-core Field permeability test
CAN-JGRC 006	Reservoir survey Installation of water quality observation hole	Midstream area (dam axis upstream)	32° 05´48.004″N 116° 49´49.137″W	3.838	4.180	4.399	50.0	9.01	5.08	All-core Grain size analysis Field permeability test
CAN-JGRC 007	Installation of water quality observation hole in downstream area	Downstream area (dam axis downstream)	32° 05´49.618″N 116° 51´25.654″W	3.841	4.379	4.588	50.0	9.01	5.08	Non-core
CAN-JGRC 009	Cut-off right bank survey	Upstream abut on dam axis right bank	32° 05´51.441″N 116° 50´38.843″W	6.951	7.210	7.567	25.5	9.01	5.08	All-core Field permeability test

To grasp the correct shape of the basement on the assumed dam axis, boring surveys were conducted at three points (CNA-JGRC001 to 003) – the riverbed on the assumed dam axis and the right and left banks. Consequently, the top face of the basement at the riverbed was found to be 55 m below the surface (altitude: -52.32 m). On the right bank, basalt and strongly weathered and cataclastic siltstones are distributed near the surface. According to the boring survey, the top-surface depth of the low-permeability siltstones was -16.60 m in altitude. This indicates that the cut-off wall construction range on the right bank requires further extension to the mountain side.

Boring surveys at two points (CNA-JGRC005 and 009) on the right-bank abutment clarified the top-surface depth of the low-permeability basement (altitude: -0.08 m) and provided reference on the extension of the cut-off wall.

Two holes (CNA-JGRC006 and 007) were bored to grasp the basement depth and aquifer properties and to observe the groundwater level and quality in the upstream and downstream catchment areas of the assumed dam axis.

These boring surveys verified that the underground valley basement around the assumed dam axis is mainly composed of siltstones. However, the results also revealed that highly permeable basalt and severely cracked siltstones were distributed in part of the basement on the right side of the assumed dam axis, indicating a complicated geologic structure. A stratum disorder by landslide partially explains the geologic structure on the right bank. Figures 4.4.6 and 4.4.7 show the geologic profile of the assumed dam axis based on the results of geological survey.

Figure 4.4.6 Geologic Profile Around the Assumed Dam Axis

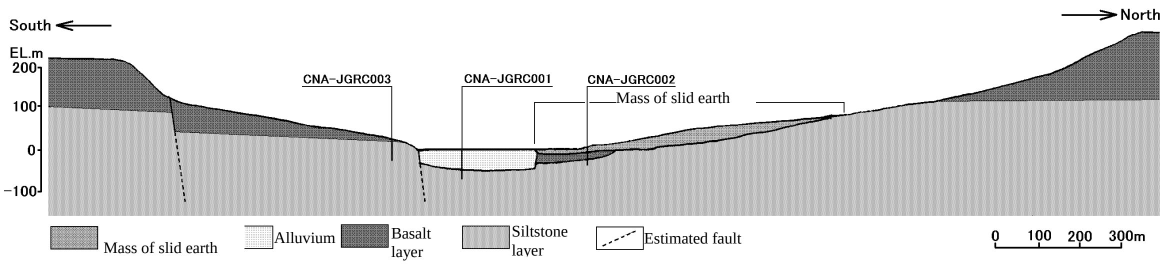
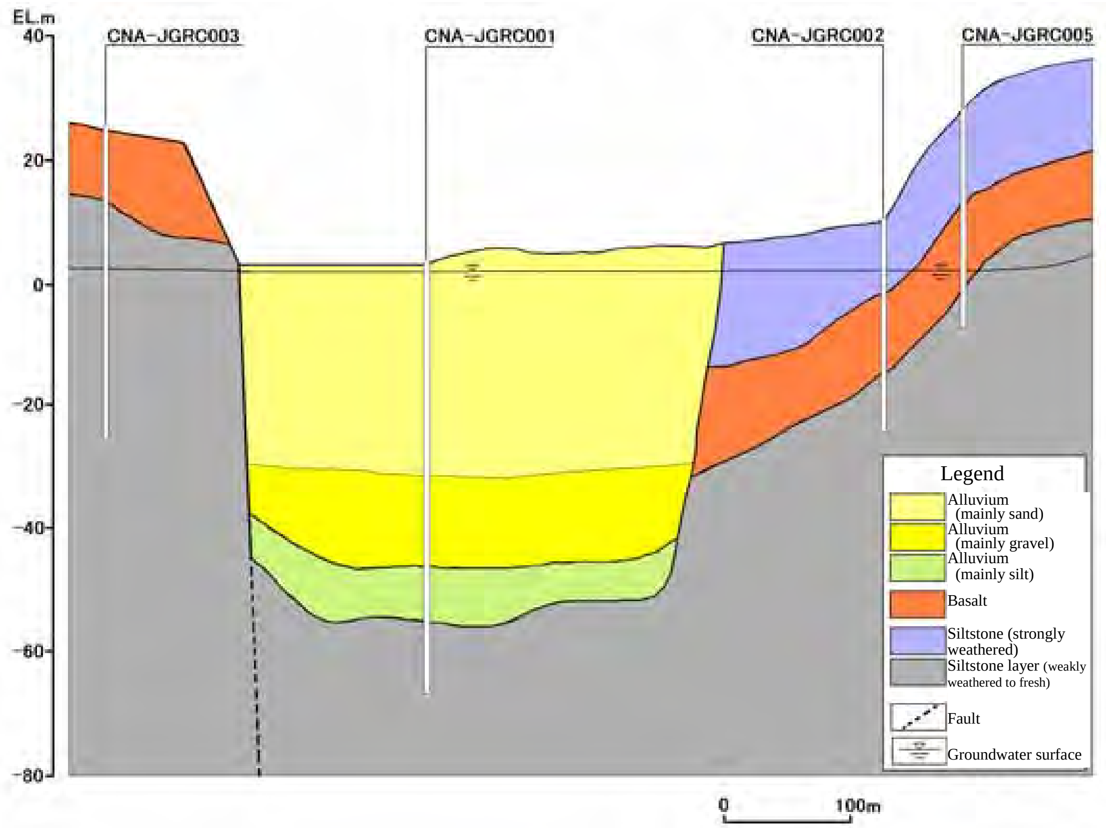


Figure 4.4.7 Geologic Profile of the Assumed Dam Axis



From the results of boring survey and electric prospecting, Figure 4.4.8 shows the top-face altitude contour of siltstones composing the basement around the assumed dam axis. Figure 4.4.9 shows a sectional view parallel with the valley.

Further analysis of the aquifer with existing well-excavation reference materials revealed that the clay-silt, fine sand, medium to coarse sand, small gravels, and medium to large gravels composing the alluvium were not spread continuously in the horizontal direction. Since it is extremely unlikely that the alluvium contains a continuous low-permeability layer of clay-silt, the groundwater in the aquifer of this region is considered as free-state groundwater forming one groundwater face. Note that existing well-excavation reference materials may judge geology from well-excavation slime or the geology description standards may not be uniform.

Figure 4.4.8 Top-face Contour Map of the Basement

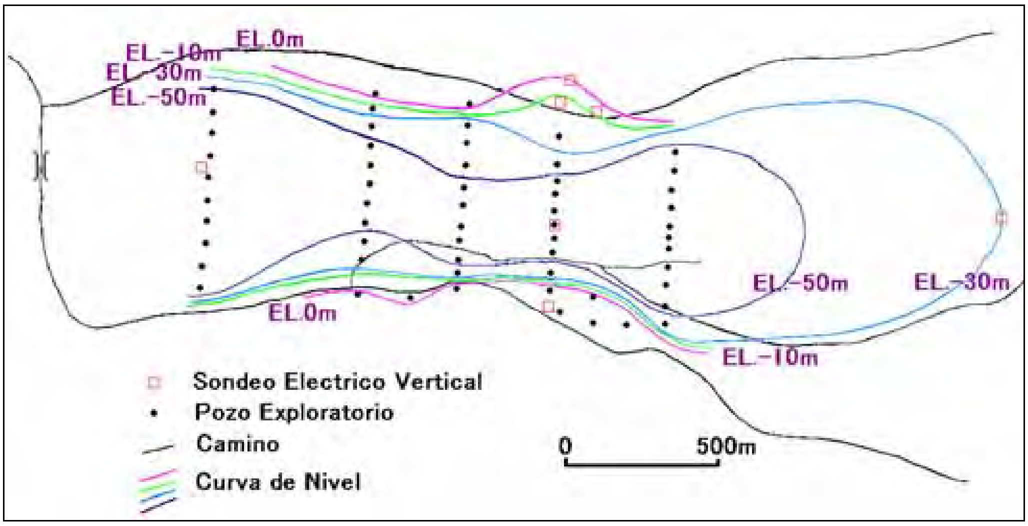
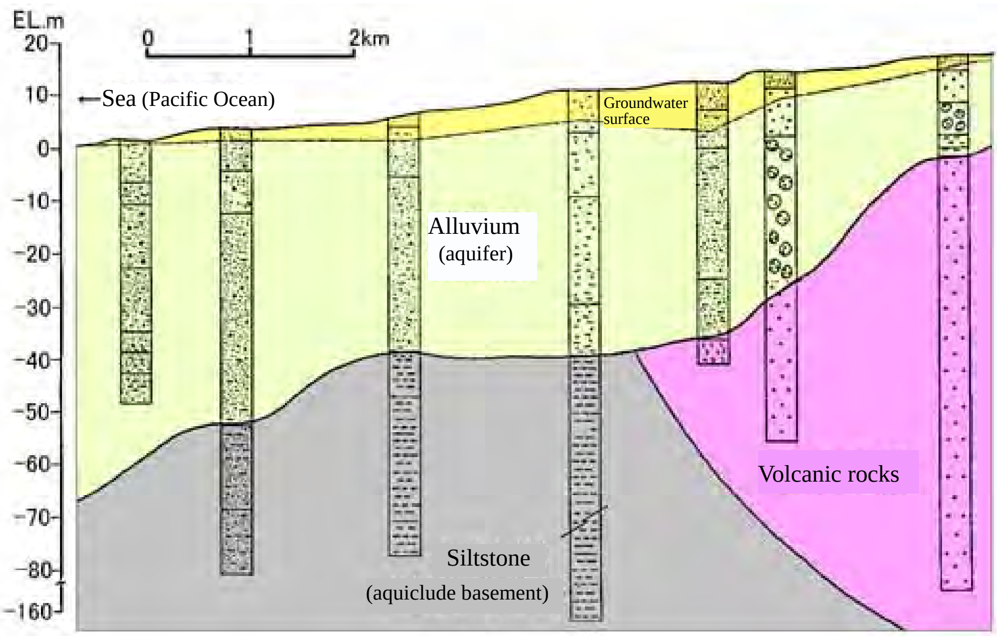


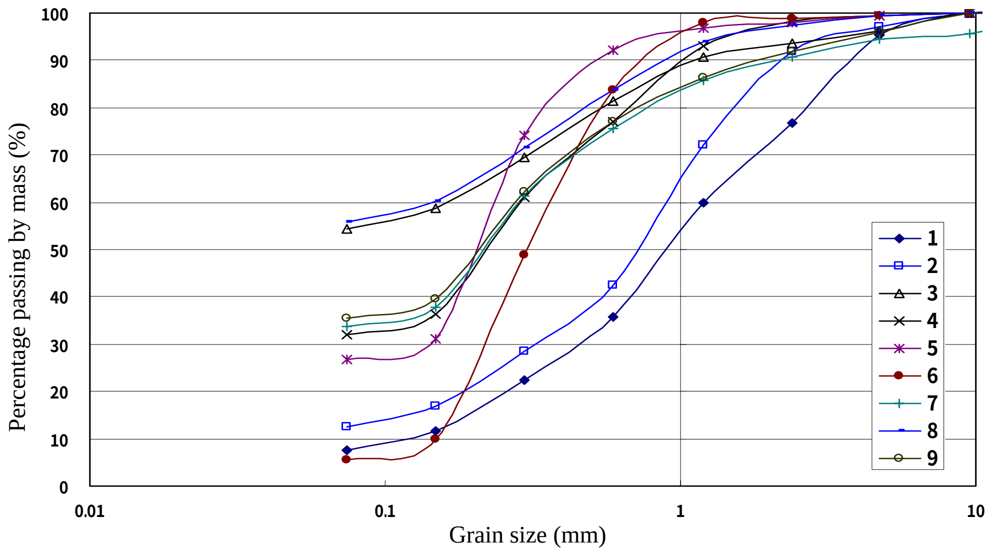
Figure 4.4.9 Longitudinal Profile of La Mision Valley



(b) Grain size analysis

Representative samples were collected from the boring core of CNA-JGRC006 and sieved for grain size analysis. Figure 4.4.10 shows the results. The alluvium at this boring point is mainly a sand layer composed of gravels and silt.

Figure 4.4.10 Grain Size Cumulative Curves of Samples from CNA-JGRC006



* Depths of sample collection

1: 3.30–3.60 m, 2: 6.10–6.40 m, 3: 11.05–11.35 m, 4: 12.10–12.40 m, 5: 15.10–15.40 m, 6: 18.10–18.40 m, 7: 21.10–21.40 m, 8: 24.10–24.40 m, 9: 31.10–31.40 m

From the above results, ground hydraulic conductivity was estimated using the methods of Matsuo and Kawano (1970), and also Creager. Table 4.4.4 lists the estimated hydraulic conductivities.

Table 4.4.4 Hydraulic Conductivity Estimated from Grain Sizes

Name of soil	Name of soil from D50	Matsuo and Kawano (1970)		Creager	In-situ permeability test
		D50	D20	D20	
		cm/S	cm/S	cm/S	cm/S
silt-bearing sand	coarse sand	3.50E-01	1.50E-02	1.60E-02	7.89E-04
silt-bearing sand	coarse sand	3.50E-01	1.50E-02	6.90E-03	2.43E-03
silt	silt				3.41E-03
silty sand	fine sand	1.50E-02			7.10E-04
silty sand	fine sand	1.50E-02			9.28E-04
silt-bearing sand	medium sand	8.50E-02	1.50E-02	6.90E-03	1.14E-03
silty sand	fine sand	1.50E-02			6.46E-04
silt	silt				7.21E-04
silty sand	fine sand	1.50E-02			4.43E-04

(c) Permeability test using borehole

Permeability tests using boreholes were performed: field permeability test for alluvium, basalt, and strongly weathered to weathered siltstones; Lugeon test for weakly weathered to fresh siltstones. For the field permeability test, the variable head method or the constant head method was used according to the permeability of the stratum. Water was injected in both methods. The hydraulic conductivity was calculated as follows:

Variable head $$k = 2.3 * C * A * \frac{\log(H_1 / H_2)}{T_2 - T_1}$$

Constant head $$k = C * Q / H$$

$$C = \frac{2.3 * log\left[l/d + \sqrt{(l/d)^2 + 1} \right]}{2 * \pi * l}$$

k: Hydraulic conductivity	A: Sectional area of water-injected section
T_1: Test start time	T_2: Test end time
H_1: Head at T_1	H_2: Head at T_2
H: Head	Q: Water supply rate
1: Length of water-injected section	d: Diameter of water-injected section

Table 4.4.5 and Figure 4.4.11 gives the results of permeability tests. Figure 4.4.11 shows the hydraulic conductivities converted from the Lugeon values with 1 Lu = 1.3×10^{-5} cm/s. The comparatively fresh siltstones were found to have low permeability and be able to form the basement of a subsurface dam. The hydraulic conductivity of the alluvium serving as a reservoir layer varies greatly from 10^{-2} to 10^{-6} cm/sec.

The relationship between geological classification and hydraulic conductivity indicates that the hydraulic conductivity decreases in order of alluvium, basalt, cataclastic siltstone, and siltstone.

Table 4.4.5 Results of Permeability Tests Using Boreholes

Borehole 001

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	Alluvium	None	2.4E-06	cm/s	
02.00 - 05.00 m	Alluvium	0.93	1.1E-05	cm/s	
05.00 - 08.00 m	Alluvium	0.87	1.4E-05	cm/s	
08.00 - 13.00 m	Alluvium	0.78	1.4E-03	cm/s	
13.00 - 18.00 m	Alluvium	0.83	1.5E-03	cm/s	
18.00 - 22.00 m	Alluvium	0.84	2.1E-06	cm/s	
22.00 - 27.00 m	Alluvium	0.84	2.1E-03	cm/s	
27.00 - 32.00 m	Alluvium	0.85	7.5E-04	cm/s	
32.00 - 37.00 m	Alluvium	0.73	5.8E-03	cm/s	
37.00 - 42.00 m	Alluvium	0.83	4.8E-03	cm/s	
42.00 - 47.00 m	Alluvium	0.83	5.2E-03	cm/s	
47.00 - 52.00 m	50.00 to silt	0.81	1.8E-04	cm/s	
52.00 - 55.00 m	Silt	0.82	3.6E-05	cm/s	
55.00 - 58.00 m	55.00 to silt	0.79	3.9E-05	cm/s	
58.00 - 61.00 m	Siltstone	0.84	1.1E-02	cm/s	
61.00 - 65.00 m	Siltstone	0.82	0.0	Lu’	Pc = 2.2 kg/cm^2
65.00 - 70.00 m	Siltstone	0.82	0.6	Lu’	Pc = 3.1 kg/cm^2

Borehole 002

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	01.30 to siltstone	None	1.1E-06	cm/s	
03.00 - 05.00 m	Siltstone		–		
05.00 - 10.00 m	Siltstone	None	0.6	Lu’	Pc = 1.9 kg/cm^2
10.00 - 15.00 m	11.00 to basalt	7.8	0.3	Lu’	Pc = 2.2 kg/cm^2
15.00 - 20.00 m	Basalt	7.8	7.8E-04	cm/s	
20.00 - 23.00 m	Basalt	7.8	2.0E-04	cm/s	
23.00 - 26.00 m	25.10 to siltstone	7.8	3.7E-03	cm/s	
26.00 - 29.00 m	Siltstone	7.8	8.8E-05	cm/s	
29.00 - 34.00 m	Siltstone	7.8	0.4	Lu’	Pc = 6.1 kg/cm^2

Borehole 003

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	01.30 to basalt	None	5.6E-04	cm/s	
03.00 - 06.00 m	Basalt	None	1.0E-04	cm/s	
06.00 - 09.00 m	Basalt	None	1.9E-04	cm/s	
09.00 - 12.00 m	Basalt	None	1.9E-04	cm/s	
12.00 - 15.00 m	12.25 to siltstone	None	1.0E-04	cm/s	
15.00 - 18.00 m	Siltstone	None	2.8E-04	cm/s	
18.00 - 21.00 m	Siltstone	None	3.3E-05	cm/s	
21.00 - 24.00 m	Siltstone	23.76	8.5E-05	cm/s	
24.00 - 27.00 m	Siltstone	23.76	4.9E-05	cm/s	
27.00 - 30.00 m	Siltstone	23.76	5.9E-05	cm/s	
30.00 - 33.00 m	Siltstone	23.76	6.1E-05	cm/s	
33.00 - 36.00 m	Siltstone	23.76	9.5E-05	cm/s	
36.00 - 41.00 m	Siltstone	23.76	1.8E-03	cm/s	
41.00 - 46.00 m	Siltstone	23.76	1.7E-04	cm/s	
46.00 - 51.00 m	Siltstone	23.76	2.2 max	Lu’	Pc = 3.5 kg/cm^2 max

Borehole 005

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	00.25 to siltstone	None	1.2E-03	cm/s	
03.00 - 06.00 m	Siltstone	None	4.4E-04	cm/s	
06.00 - 09.00 m	Siltstone	None	4.0E-04	cm/s	
09.00 - 12.00 m	Siltstone	None	1.0E-03	cm/s	
12.00 - 15.00 m	Siltstone	None	3.4E-04	cm/s	
15.00 - 18.00 m	15.50 to basalt	None	5.3E-03	cm/s	
18.00 - 21.00 m	Basalt	None	3.5E-04	cm/s	
21.00 - 24.00 m	Basalt	None	8.5E-04	cm/s	
24.00 - 27.00 m	Basalt	25.62	8.8E-04	cm/s	
28.50 - 33.50 m	27.55 to siltstone	25.62	0.1	Lu’	Pc = 4.7 kg/cm^2

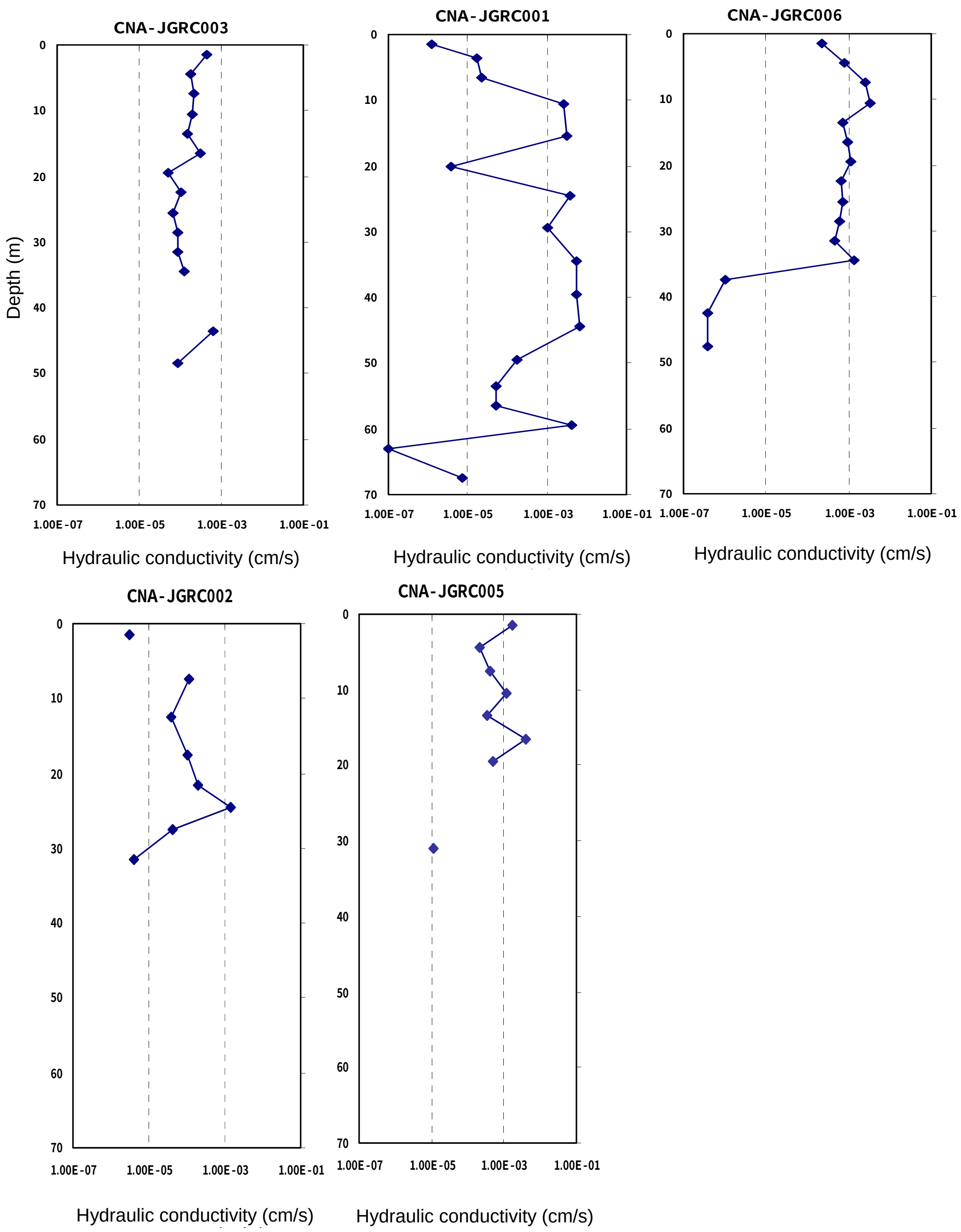
Borehole 006

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	Alluvium	1.32	1.7E-04	cm/s	
03.00 - 06.00 m	Alluvium	1.32	7.9E-04	cm/s	
06.00 - 09.00 m	Alluvium	1.32	2.4E-03	cm/s	
09.00 - 12.00 m	Alluvium	2.14	3.4E-03	cm/s	
12.00 - 15.00 m	Alluvium	1.36	7.1E-04	cm/s	
15.00 - 18.00 m	Alluvium	1.57	9.3E-04	cm/s	
18.00 - 21.00 m	Alluvium	1.32	1.1E-03	cm/s	
21.00 - 24.00 m	Alluvium	1.32	6.5E-04	cm/s	
24.00 - 27.00 m	Alluvium	1.27	7.2E-04	cm/s	
27.00 - 30.00 m	Alluvium	1.24	6.1E-04	cm/s	
30.00 - 33.00 m	Alluvium	1.26	4.4E-04	cm/s	
33.00 - 36.00 m	34.10 to siltstone	1.26	1.4E-03	cm/s	
35.00 - 40.00 m	Siltstone	1.26	0.0	Lu’	Pc = 4.1 kg/cm^2
40.00 - 45.00 m	Siltstone	1.26	0.0	Lu’	Pc = 6.2 kg/cm^2
45.00 - 50.00 m	Siltstone	1.26	0.0	Lu’	Pc = 8.2 kg/cm^2

Borehole 009

Test Section	Geology	Groundwater Level (GL-m)	Hydraulic Conductivity	Unit	
00.00 - 03.00 m	Colluvial soil	None	5.5E-06	cm/s	
03.00 - 06.00 m	Colluvial soil	5.15	4.0E-04	cm/s	
06.00 - 09.00 m	Colluvial soil	5.17	2.1E-03	cm/s	
09.00 - 12.00 m	11.30 to siltstone	5.23	8.9E-04	cm/s	
12.00 - 15.00 m	Siltstone	5.13	2.1E-04	cm/s	
15.50 - 20.50 m	Siltstone	5.15	0.0	Lu’	Pc = 4.6 kg/cm^2
20.50 - 25.50 m	Siltstone	5.17	3.3	Lu’	Pc = 2.6 kg/cm^2

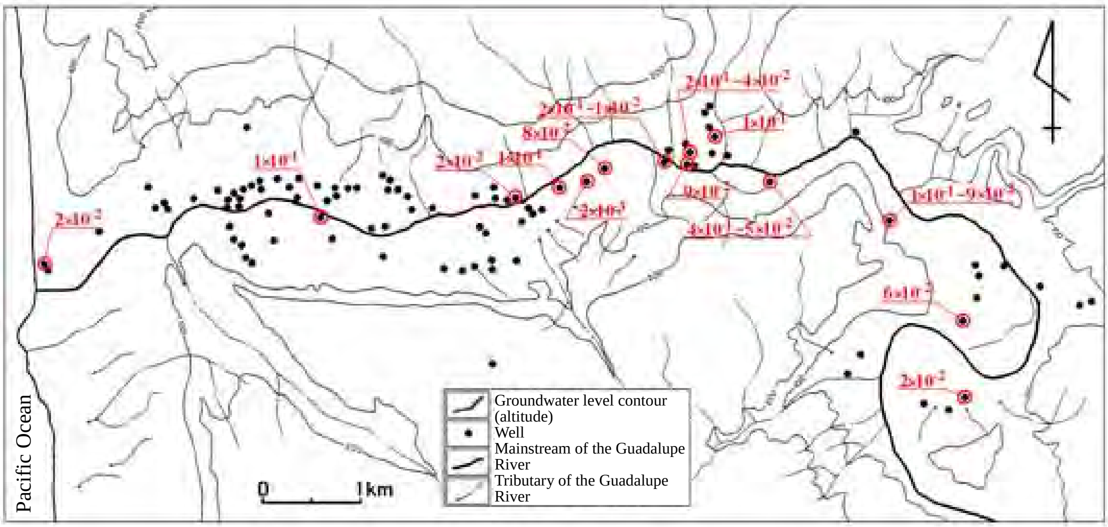
Figure 4.4.11 Results of Permeability Tests Using Boreholes



(d) Pumping test

Pumping tests are performed at many wells in this region. Figure 4.4.12 shows the locations of the tested wells and their conductivities obtained by pumping tests.

Figure 4.4.12 Hydraulic Conductivity Distribution Map of Wells by Pumping Tests (Unit: cm/s)



Hydraulic conductivity of the alluvium estimated from the results of grain size analyses and pumping tests are of the order from 10^{-1} to 10^{-3} cm/sec. This indicates that the alluvium has adequate permeability as an aquifer. To the contrary, hydraulic conductivity obtained by field permeability tests are of orders one or two smaller. Field permeability tests often show slightly smaller hydraulic conductivities presumably due to the following reasons:

- Since water is injected for the field permeability test, the borehole wall may become clogged with fine particles at water injection. Or, the borehole may become clogged at boring.
- The test section scale is generally greater for a pumping test than for a field permeability test. In other words, the results of a field permeability test are affected by local permeability but those of a pumping test reflect the mean permeability of a wider aquifer.

4.4.4 Meteorological and hydrological surveys

The Guadalupe River has 11 meteorological observation points (see Figure 4.4.1) and 2 river flow rate observation points in the catchment area. For this survey, one meteorological observation point and one river flow rate observation point were newly added to La Mision. Table 4.4.6 lists meteorological and hydrological data collected and observed in this survey. The meteorological observation items are temperature, precipitation, gage evaporation, wind direction, and wind speed.

Table 4.4.6 Meteorological and Hydrological Data

Precipitation

No.	Observation Point	Latitude	Longitude	Daily Data Period	80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02
1	Agua Caliente(No.64)	32°06′08″	116°27′14″	1969/1/1～2002/6/30	
2	El Porvenir(No.149)	32°05′00″	116°38′00″	1988/11/7～2002/6/30	
3	Ignacio Zaragoza(No. 65)	32°11′43″	116°29′08″	1964/12/1～2002/6/30	
4	Olivares Mexicanos(No.26)	32°02′57″	116°36′51″	1954/3/1～1999/7/31	
5	Santa Rosa(St.ID,2005)	32°04′	116°45′	1948/4/1～1987/11/30	
6	Ensenada(St.ID,2072)	31°53′	116°36′	1923/1/1～2002/6/30	
7	El Compadre(St.ID,2019)	32°09′	116°15′	1948/1/1～1975/12/31	
8	El Pinal(St.ID,2021)	32°11′	116°17′	1969/1/1～1989/12/31	
9	Ojos Negros(St.ID,2035)	31°52′	116°16′	1948/1/1～1989/12/31	
10	Real Del Castillo(St.ID,2122)	31°57′	116°18′	1980/1/1～1989/12/31	
11	Valle De San Rafael(St.ID,2118)	31°55′	116°14′	1979/1/1～1989/12/31	
12	La Mision(No. 152)	32°06′07"	116°48′40"	2000/1/1～2002/6/30	

Temperature

No.	Observation Point	Latitude	Longitude	Daily Data Period	80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02
1	Agua Caliente(No.64)	32°06′08″	116°27′14″	1969/1/1～1999/4/31, 1999/8/1～2002/6/30	
2	El Porvenir(No.149)	32°05′00″	116°38′00″	1988/1/1～2002/6/30	
3	Ignacio Zaragoza(No. 65)	32°11′43″	116°29′08″	1964/12/1～1999/3/31	
4	La Mision(No. 152)	32°06′07"	116°48′40"	2000/1/1～2002/6/30	
5	Olivares Mexicanos(No.26)	32º02' 57"	116º36' 51"	1954/3/1～2000/9/30	
6	Santa Rosa(St.ID,2005)	32°04′	116°45′	1948/4/1～1987/11/31	
7	Ensenada(St.ID,2072)	31°53′	116°36′	1923/1/1～2002/6/30	

Evapotranspiration

No.	Observation Point	Latitude	Longitude	Daily Data Period	80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02
	Agua Caliente(No.64)	32°06′08″	116°27′14″	1970/1/1～1999/4/31, 1999/8/1～2002/6/30	
2	El Porvenir(No.149)	32°05′00″	116°38′00″	1990/12/1～2002/6/30	
3	Ignacio Zaragoza(No. 65)	32°11′43″	116°29′08″	1964/12/1～1999/3/31	
4	La Mision(No. 152)	32°06′07″	116°48′40"	2000/2/1～2001/11/30, 2002/1/1～2002/6/30	
5	Olivares Mexicanos(No.26)	32°02′57″	116°36′51″	1954/9/1～1989/10/31	
6	Santa Rosa(St.ID,2005)	32°04′	116°45′	1962/1/1～1979/3/31	
7	Ensenada(St.ID,2072)	31°53′	116°36′	1923/1/1～2002/6/30	

River Flow Rate

No.	Observation Point	Latitude	Longitude	Daily Data Period	80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02
1	Santa Rosa(St.ID,1027)	32°01′07″	116°45′03″	1948/3/1～1999/12/31, 2000/7/1～2002/2/20	
2	Agua Caliente(St.ID,1023)	32°06′47″	116°27′02″	1948/3/1～1999/12/31	
6	La Zorra	-	-	2000/3/1～2002/2/20	

(1) Meteorological survey

(a) Precipitation

The mean annual precipitation at each point in the catchment area is about 300 to 400 mm. The precipitation fluctuates greatly and may even exceed 500 mm, well over the annual precipitation, every few years. This kind of rainfall pattern has an extreme effect on groundwater fluctuation with the passage of time.

Figure 4.4.14 shows the mean monthly precipitation at each observation point from 1970 until 1989 and from 1990 until 2001. At all the points, the monthly precipitation is high in October to April and low in May to September. Especially during June to August, almost no precipitation is observed.

When the correlation of precipitation between observation points was observed, the monthly precipitation showed greater correlation between closer observation points. In other words, the monthly precipitation does not differ greatly between adjacent observation points. The daily precipitation, however, did not show any clear correlation between observation points. The correlation between observation points becomes an index for estimating rainfall in a missing period.

Figure 4.4.13 Transition of Annual Precipitation at Olivares Mexicanos

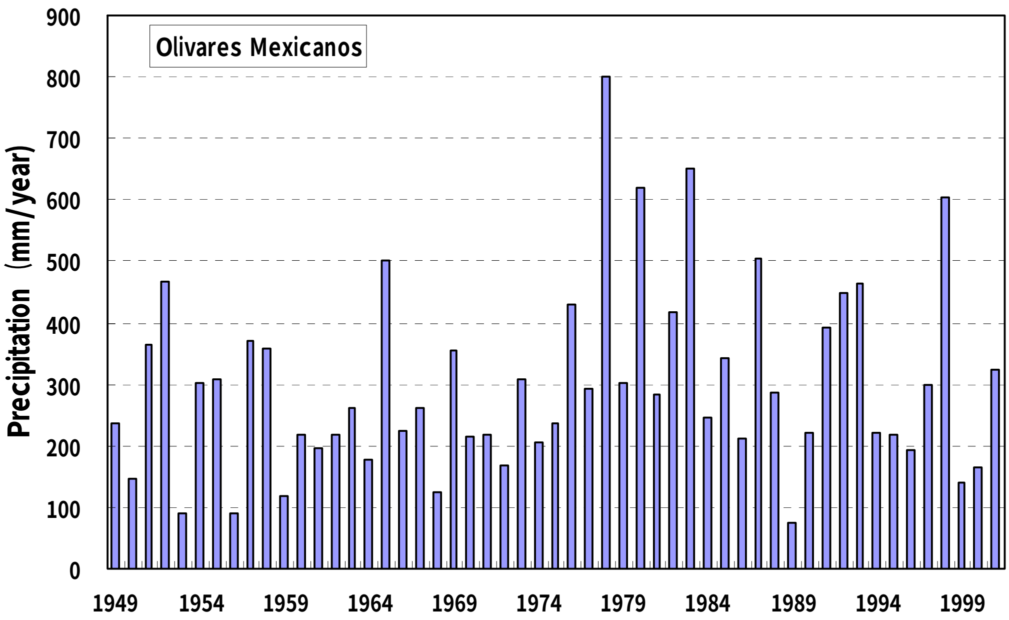
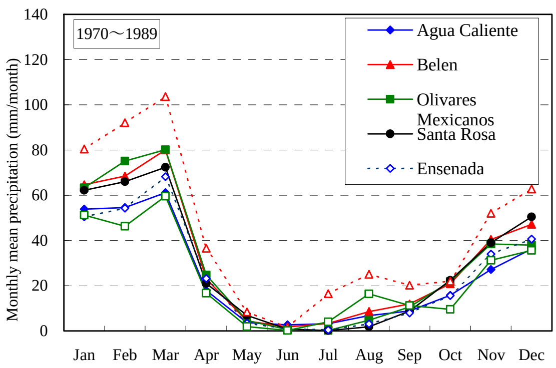
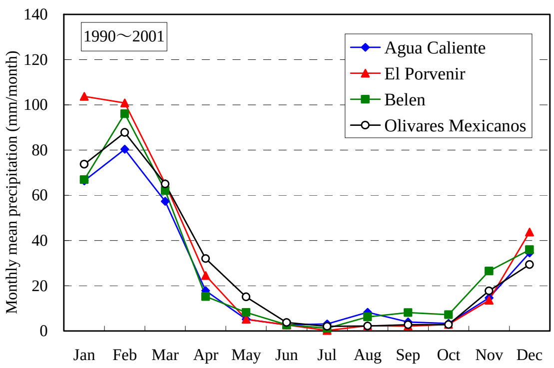


Figure 4.4.14 Mean Monthly Precipitation at Each Observation Point

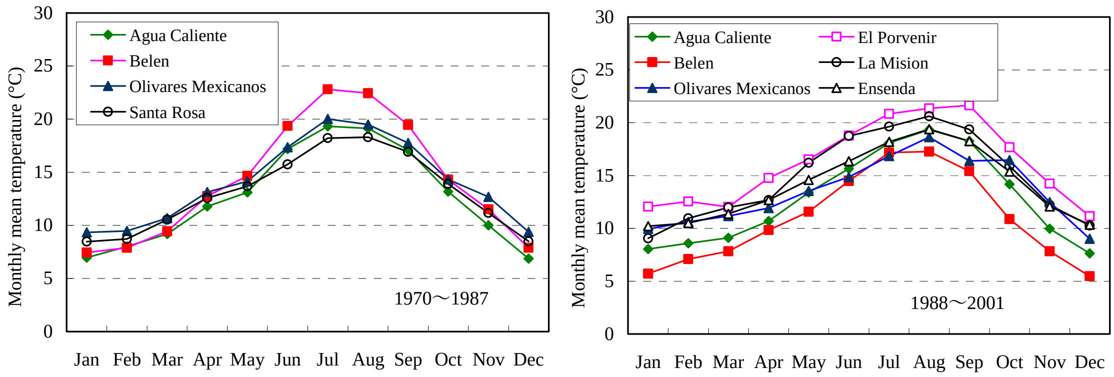




(b) Temperature

Observation data for temperature is collected from seven points. Figure 4.4.15 shows the monthly mean temperatures in 1970 to 1987 and in 1988 to 2001.

Figure 4.4.15 Monthly Mean Temperatures

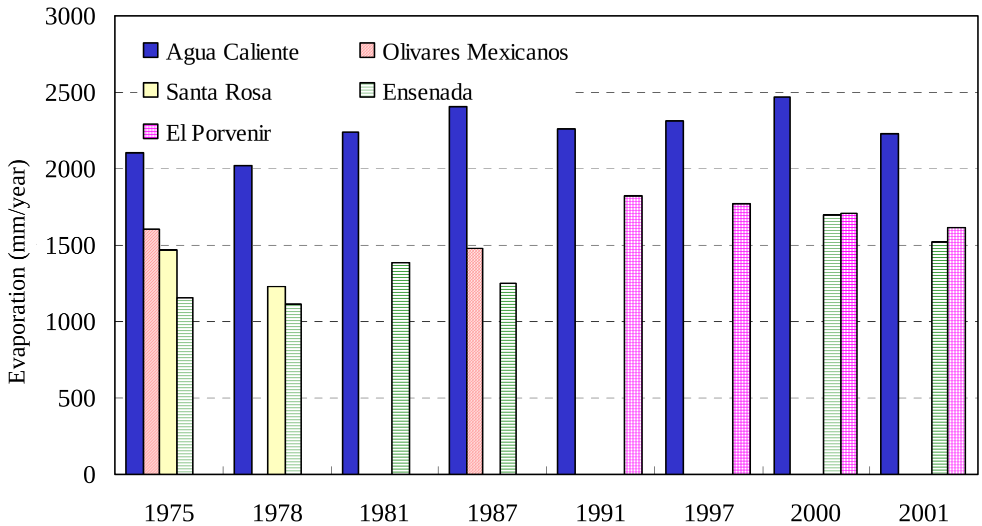


A temperature difference between observation points is mainly attributable to the difference in altitude. As the altitude rises 100 m, the temperature falls about 0.7°C. This almost matches the general tendency (0.6°C down for every 100 m up).

(c) Evapotranspiration

In the vicinity of La Mision, the evaporation is observed with pan evaporation gages over a long period of time at four points: Agua Caliente, El Porvenir, Olivares Mexicanos, and Ensenada. Figure 4.4.16 compares the annual gage evaporation between the observation points. The observed value tends to be greater at a point further inland.

Figure 4.4.16 Transition of Annual Gage Evaporation



The methods of obtaining potential evapotranspiration are as follows:

- Calculation from observed gage evaporation by using an empirical coefficient based on the wind velocity and gage type

  (Potential evapotranspiration) = Empirical coefficient (0.6 - 0.8) × (gage evaporation)

- Estimation from temperature data

Thornwaite equation: $Ei = 16(10Ti/I)^{\alpha}N/12$

$$\alpha = 0.000000675I^3 - 0.000077I^2 + 0.01782I+0.49239$$

$$I = \sum_{i=1}^{12} (Ti/5)^{1.514}$$

Hamon equation: $Ei = 0.14(N/12)^2 qi$

Ei: Daily mean potential evapotranspiration (mm/day) in Month i

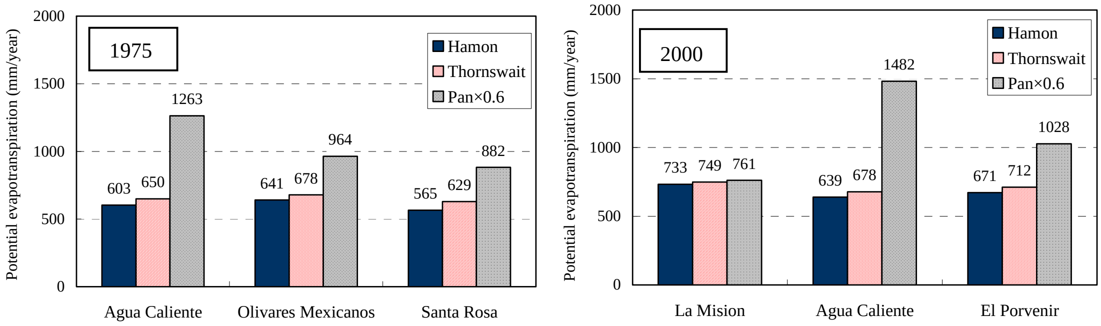
N: Possible duration of sunshine (hr) in Month i

qi: Absolute saturated humidity at daily mean temperature (g/m^3)

Ti: Mean temperature (°C) in Month i

Potential evapotranspiration values obtained by each method (where gage evaporation is multiplied by a coefficient of 0.6) are shown in Figure 4.4.17, in which annual totals between 1975 and 2000 are compared. From the figure, we see that the value estimated from gage evaporation is greater than that estimated from temperature at all points.

Figure 4.4.17 Comparison of Estimated Potential Evapotranspiration



(2) River flow rate survey

The flow rate of the Guadalupe River is observed at Agua Caliente and Santa Rosa. At these observation points, a water level / flow rate curve is obtained by flow velocity measurement and river cross-sectional surveying. The river water level is measured once a day with a leveling rod installed in the river and then the flow rate is calculated.

At Agua Caliente in the midstream of the Guadalupe River, the flow rate increases in winter and decreases in summer. This corresponds to 9.7% of the total precipitation (m^3) multiplied by the catchment area size at Agua Caliente.

Figure 4.4.18 shows the monthly mean river flow rate and the monthly precipitation at Santa Rosa. At this point, the river flows only for a short period after heavy rainfall and scarcely flows at all in a year of small precipitation. This is because the potential evapotranspiration is much greater than the precipitation and a large amount of surface water is lost by evapotranspiration. Also, a great deal of river water permeates into the ground through the groundwater basin located upstream from this region and is consumed by pumping.

The area about 5 km downstream from Santa Rosa was inundated to about 1.4 m deep with river water from Santa Rosa at rainfalls in 1978 to 1983. In the case of heavy rainfall that occurs about once in 10 years, water flows over the surface of the downstream catchment area of the Guadalupe River. In normal years, however, all river water from Santa Rosa permeates into the ground.

Figure 4.4.18 River Flow Rate at Santa Rosa

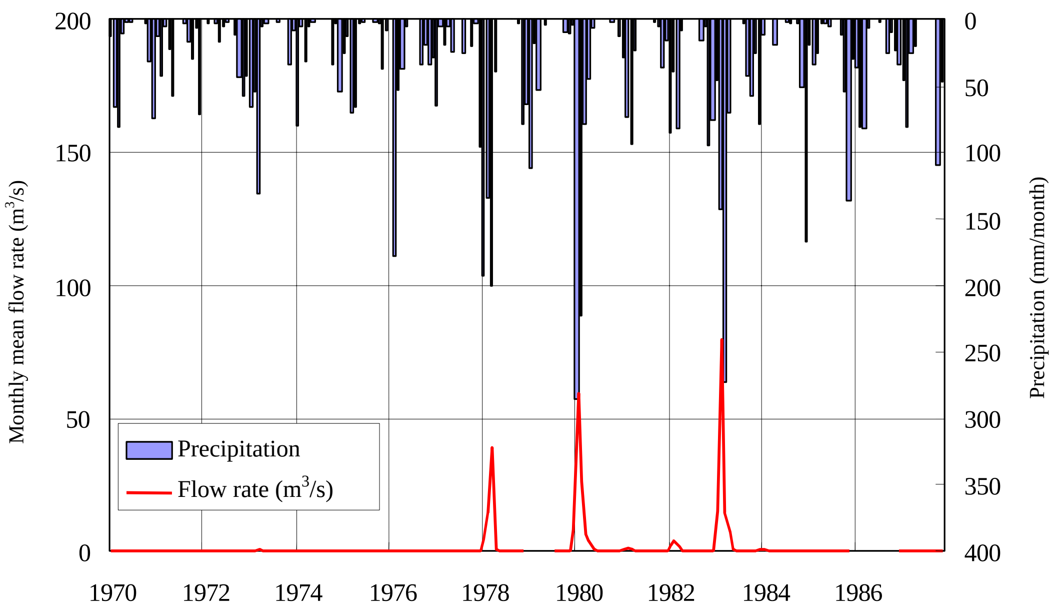
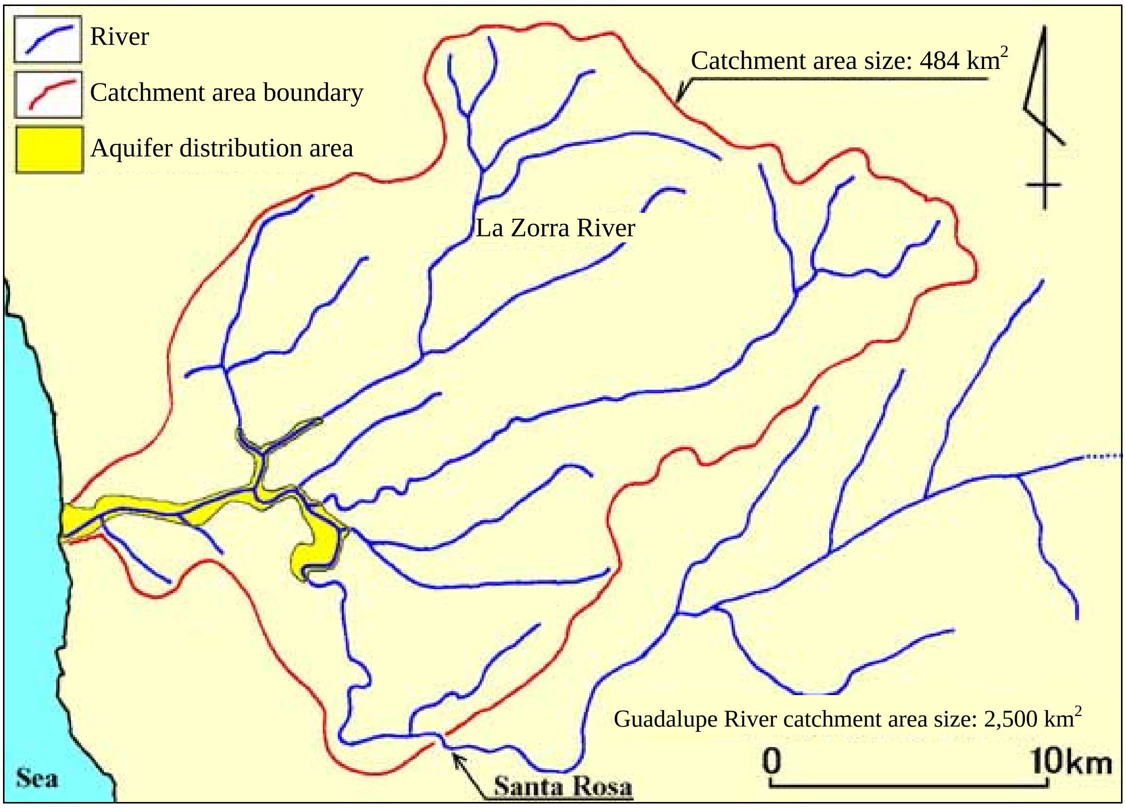


Figure 4.4.19 shows the river distribution in the vicinity of La Mision. At Santa Rosa, the Guadalupe River has a rock bed exposed narrow area where the river flow rate is observed. Around this point is a rock bed zone with almost no groundwater flow from the upstream catchment area. Only the river water should be considered for the water balance. In addition, the river water is rarely observed. Therefore, the object catchment area of this survey is limited to the range of about 484 km^2 downstream from Santa Rosa.

Regarding the flow rate of the maximum tributary (La Zorra River) of the Guadalupe River in the above range, the residents say that water had occasionally flowed in near the confluence but has not done so since 1993. In the catchment area of La Zorra River, no groundwater is used. From the rainfall at the catchment area of La Zorra River in normal and dry years, the water remaining after evapotranspiration is presumed to flow into the aquifer in La Mision entirely as groundwater.

In the area within several kilometers from the mouth of the Guadalupe River, the groundwater may flow into the Guadalupe River if the groundwater level is comparatively high. If little rainfall continues for several years, however, the groundwater level will drop. Since there is no river water, the seawater (saltwater) may run up the river and permeate into the ground.

Figure 4.4.19 Survey Catchment Area in La Mision



(3) Groundwater use survey

In the catchment area of the Guadalupe River, there are three large-scale aquifers upstream from La Mision where the groundwater is well used. Table 4.4.7 lists groundwater yields from major aquifers in the catchment area of the Guadalupe River.

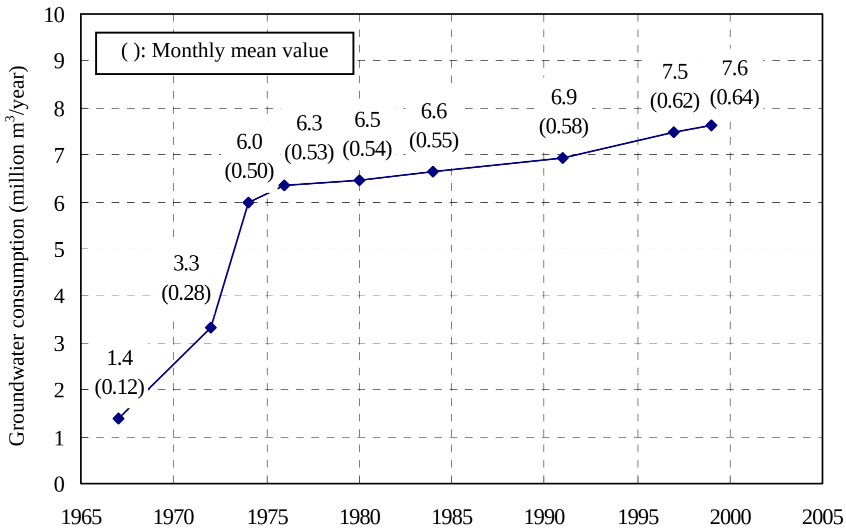
Table 4.4.7 Groundwater Yields from Aquifers in the Catchment Area of the Guadalupe River

<table>
<tr><td>Aquifer</td><td colspan="2">Groundwater Yield (Unit: million m³)</td></tr>
<tr><td>Real del Castillo</td><td>11.18</td><td rowspan="3">Total from three aquifers: 59.01
Incl. 6.50 for tap water
52.51 for farming</td></tr>
<tr><td>Ojos Negros</td><td>25.52</td></tr>
<tr><td>Guadalupe</td><td>22.31 (15.5 for farming, 6.5 for tap)</td></tr>
<tr><td>La Mision</td><td colspan="2">6.80</td></tr>
</table>

The main water source in La Mision is groundwater that is used for tap water, farming, and various other purposes. Using groundwater requires permission. Since the water quota is determined according to the purpose of use, the groundwater yield can be calculated from this quota.

La Comision Nacional del Agua (CNA), which manages groundwater, conducted fact-finding surveys on groundwater use and estimated annual yields from 1938 to 1999. Figure 4.4.20 shows the transition of annual yield since 1965.

Figure 4.4.20 Transition of Annual Groundwater Consumption

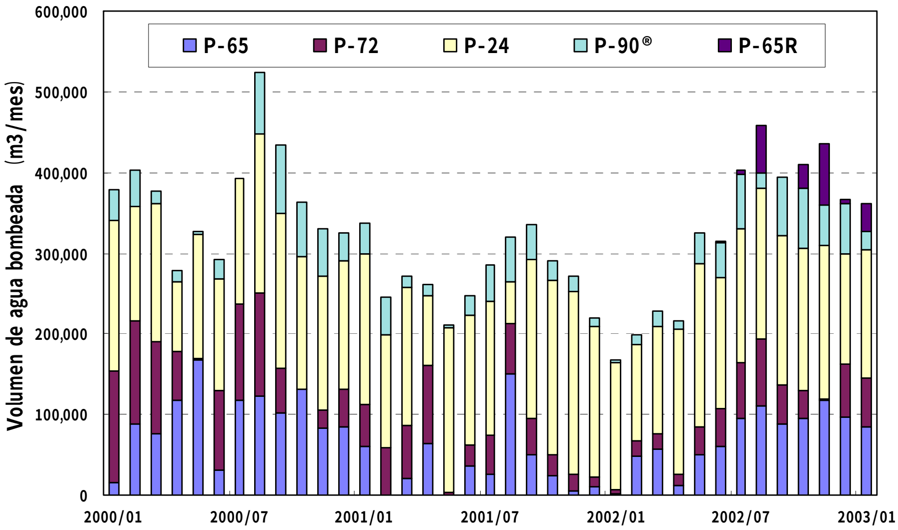


For all wells existing in the region, fact-finding surveys on groundwater use were conducted as follows:

- Waterworks

La Comision Estatal de Servicios Publicos de Ensenada (CESPE) sends water pumped from five drinking wells in La Mision to cities (Ensenada, Tijuana, etc.) tens to hundreds of kilometers away. The total annual yield permitted to CESPE is about 4,730,000 m^3. The yields from these wells are recorded by month and their data is also available. Figure 4.4.21 shows the yields from the drinking wells from January 2000 to January 2003. The figure reveals that the yields increase in the summer of a year when it does not rain much.

Figure 4.4.21 Transition of Monthly Yields from Drinking Wells



- Farming wells

The yield from a farming well was estimated from the unit water quantity and planting area by produce. Agricultural produce is usually planted two times a year. The necessary water quantity differs depending on the season; about 80% of the annual irrigation water is used from March to July. The unit water quantity for agricultural produce is clarified for each kind and also used by CNA to determine a quota. For livestock, the daily necessary water quantity is clarified for one of each kind. The yield for livestock was estimated from the daily necessary water quantity and the number of individuals of each kind.

- Household wells

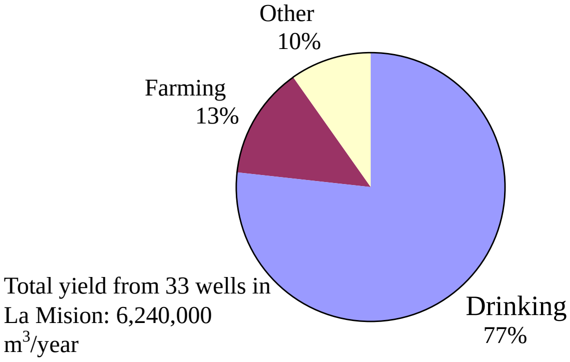
The yield from a household well was estimated from the number of users and the necessary water quantity per user.

The results of the above surveys are summarized below.

There are 77 wells in total, 57 of which are actually used. Figure 4.4.22 shows the number of wells for each use and the ratio of yield. Farming wells number more than other wells and account for about 40%.

Intake from the five drinking wells of CESPE accounts for nearly 80% of the total.

Figure 4.4.22 Groundwater Uses (CNA Survey for 1998 to 1999)



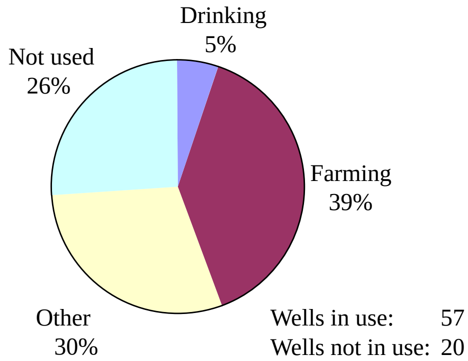
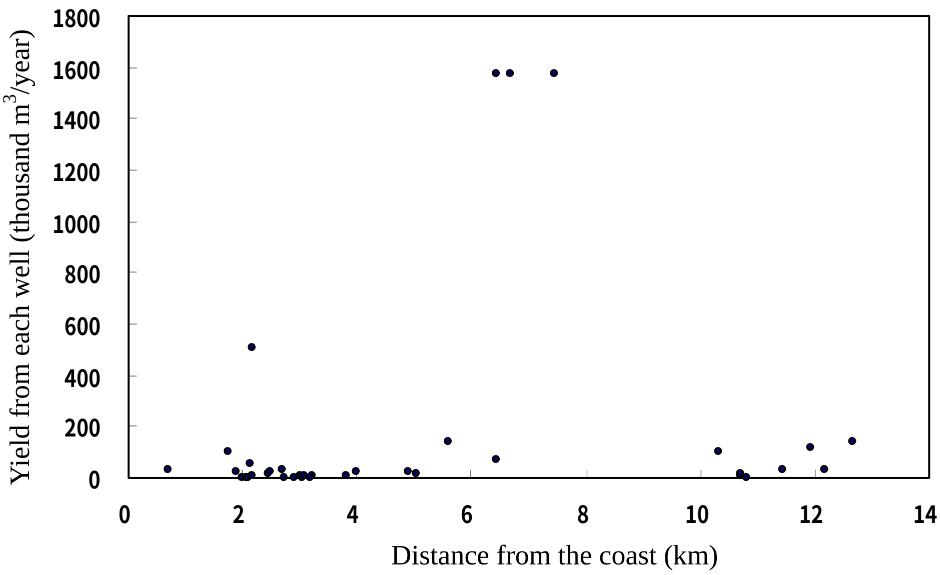


Figure 4.4.23 shows the relationship between the annual yield from each well and the distance from the coast. The wells with great yields located 6 to 8 km from the coast (junction of the largest tributary of the Guadalupe River, La Zorra River) are the drinking wells of CESPE.

Many wells are within 2 to 4 km from the coast.

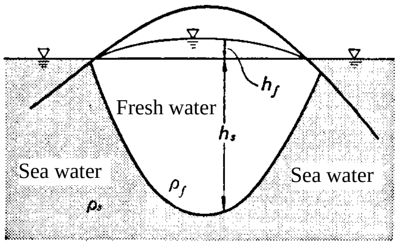
Figure 4.4.23 Yields from Wells and Distances from the Coast



(4) Groundwater level observation

In general, fresh water (groundwater of relatively low electric conductance) forms a lens on seawater (groundwater of high electric conductance) by the difference of specific gravity (Figure 4.4.24). If the groundwater level falls, the lens thickness decreases. In a region where saltwater infiltration into groundwater is anticipated, it is necessary to obtain the precise positional relationship between the groundwater level and the mean seawater level. Therefore, it is a prerequisite to accurately determine the pipe-head altitude (altitude difference from the seawater surface) of a well for groundwater level observation.

Figure 4.4.24 Illustration of Fresh Water Lens



$$hs / hf = \rho f / (\rho s - \rho f) = 40$$

hs: Thickness of fresh water (brackish water) on the seawater

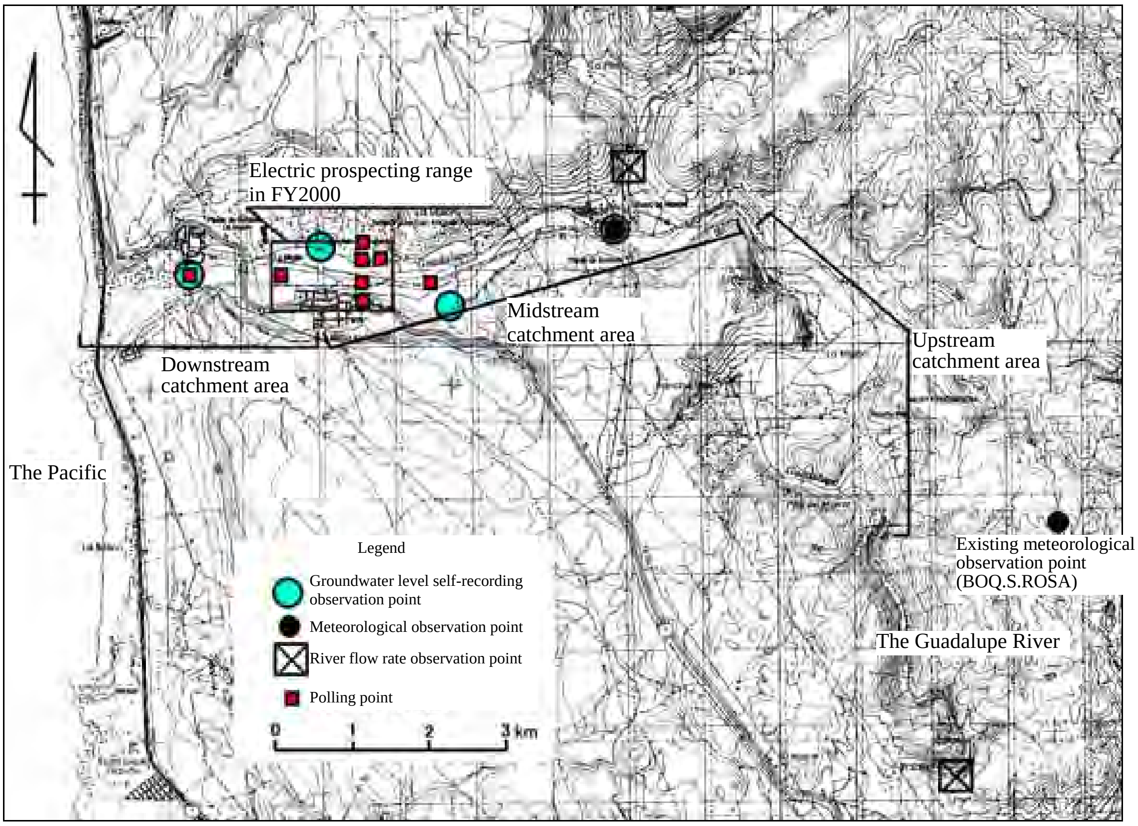
hf: Thickness of fresh water (brackish water) under the seawater

ρs: Specific gravity of the seawater = 1.025

ρf: Specific gravity of fresh water (brackish water) = 1.000 – 1.008

Groundwater level observation can be classified into continuous observation for tracking the groundwater level in time series and simultaneous water measurement for checking the plane shape of groundwater periodically. Before the start of surveying, the wells were sorted for respective observation. Figure 4.4.25 shows the groundwater level self-recording (continuous) observation points.

Figure 4.4.25 Location Map of Hydrological Observation Points



Batch measurement of the groundwater level has been performed intermittently since the 1970s. In 1999, the frequency was changed to four times a year. The measuring points total about 30. The observation holes include ones for pumping. Therefore, the groundwater level is basically measured when the well water level has recovered to close to the natural level after pumping is stopped.

An electronic water gage was used for continuous measurement of the groundwater level. This is a submerged probe consisting of a hydraulic water level sensor and various other sensors, a data logger, a memory device, and a battery and is installed below the water surface of a well. The observation equipment installed at the point furthest downstream is set for observing not only the groundwater level but also the electric conductivity, temperature, and pH to check the trend of salinization. Observation was initiated in 2000.

As an example achievement of simultaneous groundwater level observation, Figure 4.4.26 shows a groundwater level contour map as of October 2000. The groundwater level is about 0 m in altitude near the coast but rises as the distance from the coast increases. Figure 4.4.27 shows the relationship between the groundwater level and the distance from the coast. In general, the groundwater levels in October 2000 are about 2 to 5 m lower than those in November 1979.

Figure 4.4.26 Groundwater Level Contour Map (October 2000)

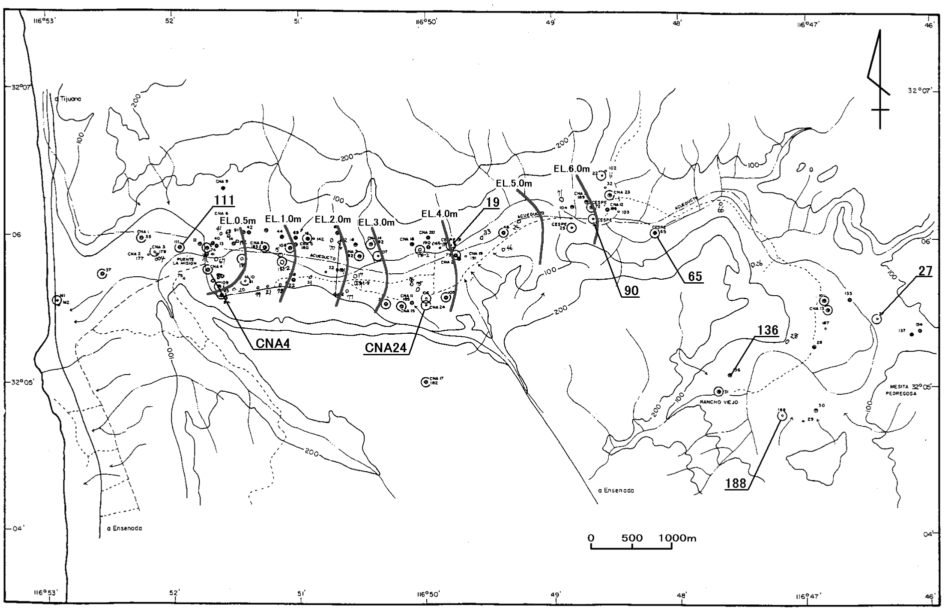


Figure 4.4.27 Relationship between Groundwater Level and Distance from the Coast

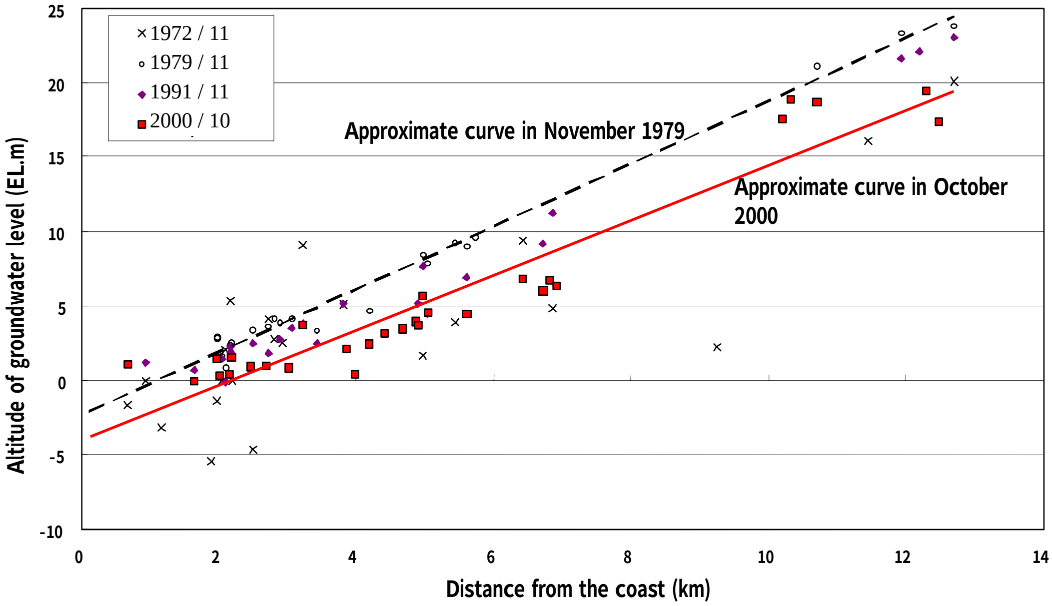
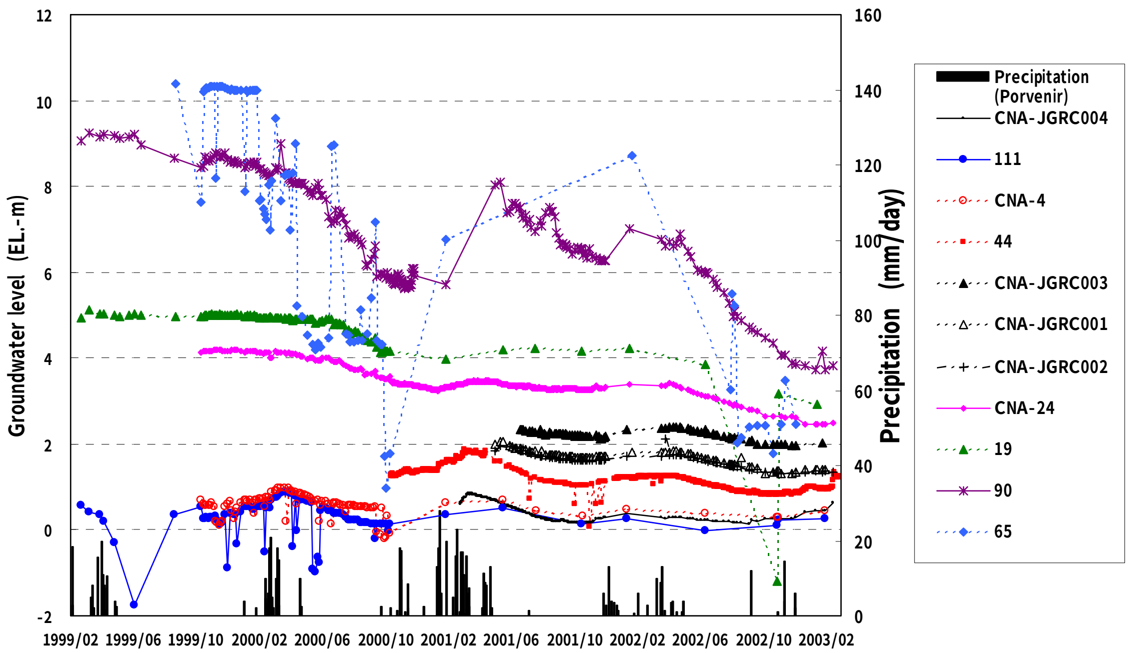


Figure 4.4.28 shows the correlation between the groundwater level fluctuation since February 1999 and the monthly precipitation at El Porvenir. The groundwater level, which fluctuates with the amount of rainfall, is high in the rainy season from November to March and low in the dry season. These days, the groundwater level generally tends to fall. This tendency seems mainly attributable to the fact that the rainfall in the rainy season was less than in normal years.

Figure 4.4.28 Recent Groundwater Level Fluctuation

(Downstream to midstream)



(Upstream to furthest upstream point)

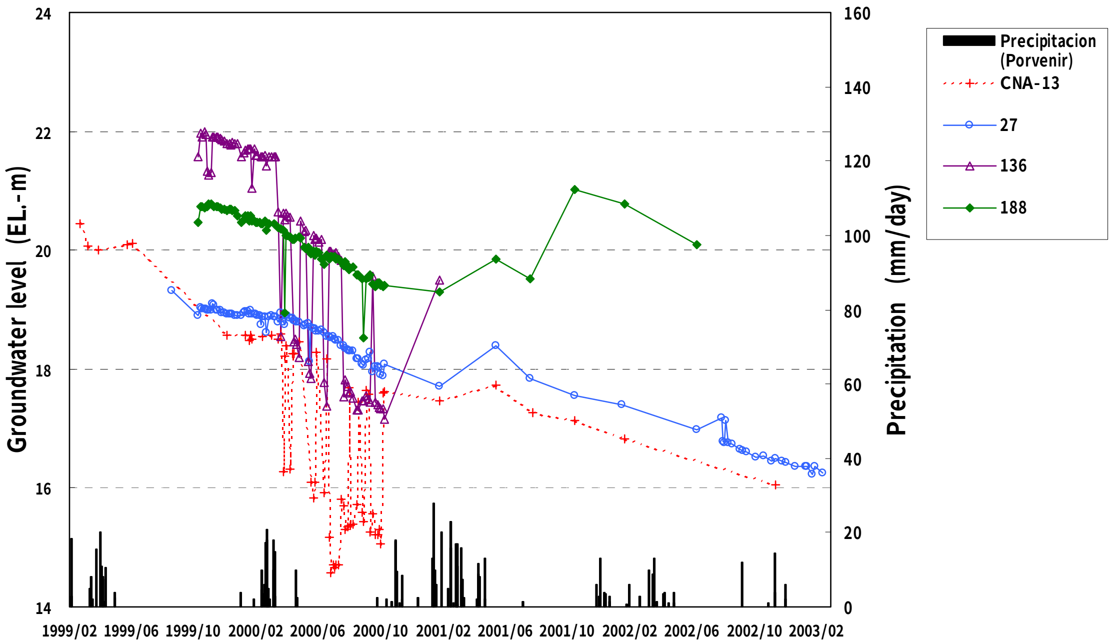
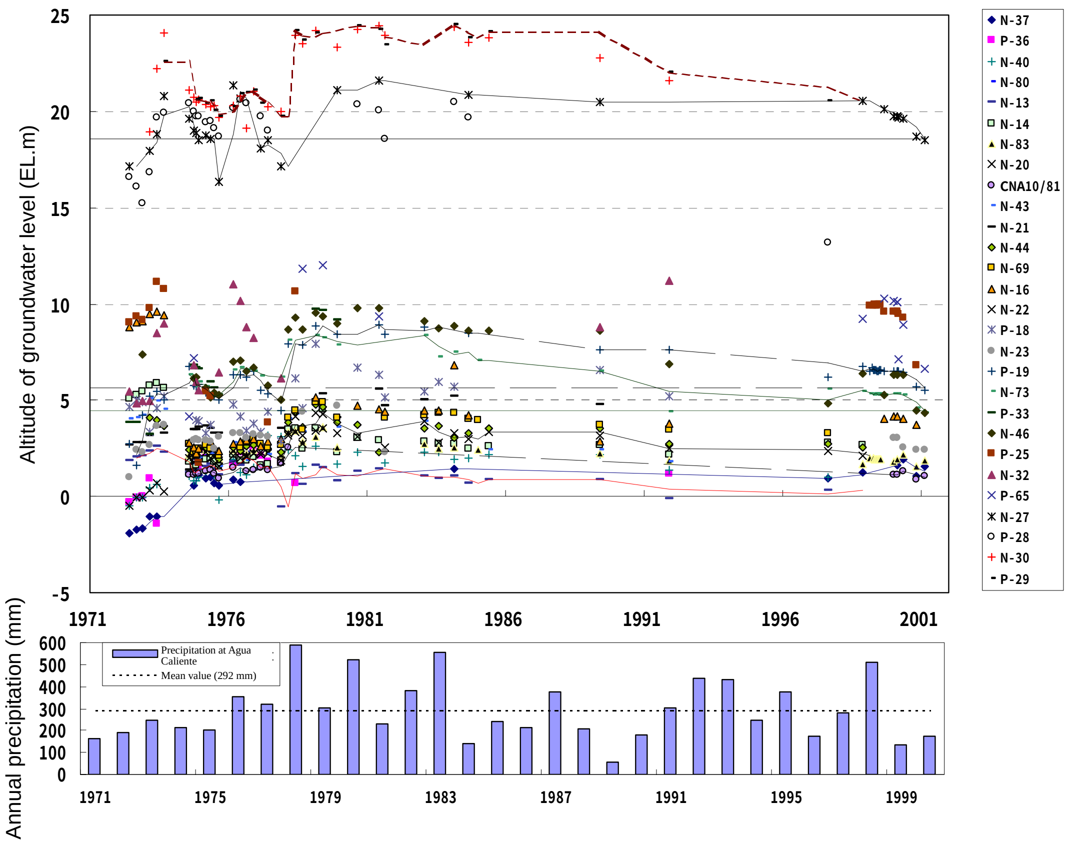


Figure 4.4.29 shows the long-term fluctuation of the groundwater level since 1972. The groundwater level was low from 1971 until 1977, showed a quick rise in 1978, and remained comparatively high until 1983. Details are unknown after 1986 because not enough data is available. However, it looks as if the groundwater level still tends to fall.

Figure 4.4.29 Long-term Fluctuation of the Groundwater Level

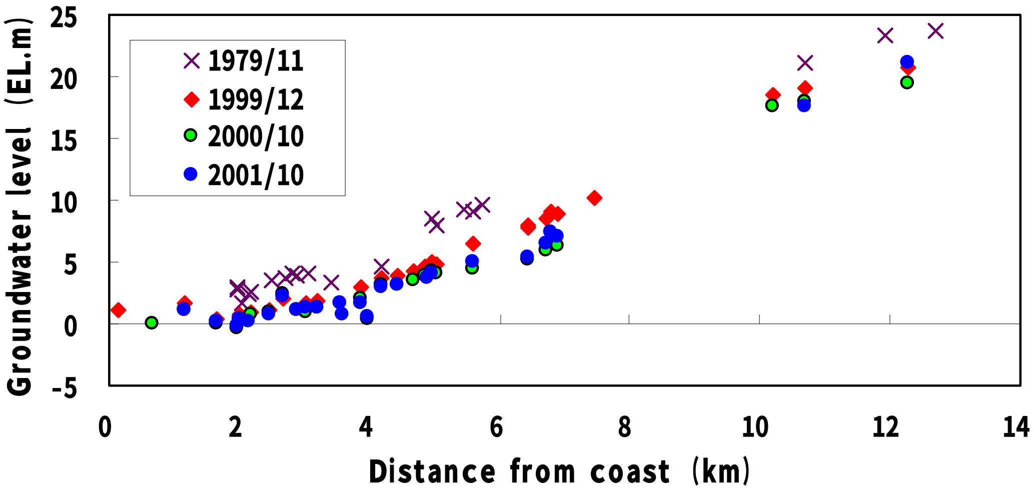


(5) Water survey

The electric conductivity of groundwater is proportional to the dissolved ion concentration. Where groundwater salinization poses a problem, the groundwater salinity can be checked with comparative ease by measuring the electric conductivity of groundwater. Sensors of portable measuring equipment were inserted into a well to measure the electric conductivity and water temperature. In this survey, the cord was extended to 50 m to enable measurement up to 50 m deep.

Figure 4.4.30 shows the relationship between the electric conductivity and groundwater level and the distance from the coast. In addition, Figure 4.4.31 (longitudinal profile) and Figure 4.4.32 (plane) show the electric conductivity of groundwater. Figure 4.4.33 shows the electric conductivity of groundwater with the passage of time.

Figure 4.4.30 Relationship between the Distance from the Coast and the Groundwater Level and Electric Conductivity



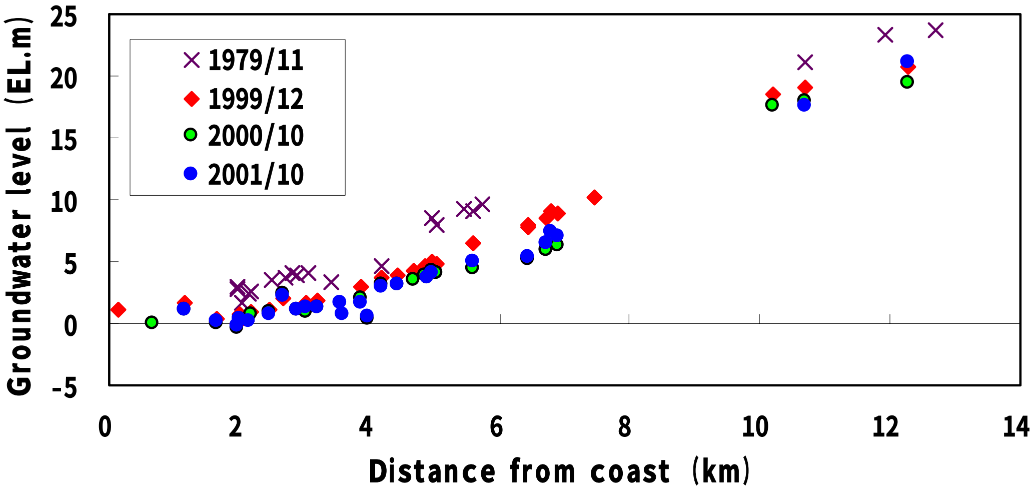


Figure 4.4.31 Electric Conductivity Distribution of Groundwater (Longitudinal Profile)

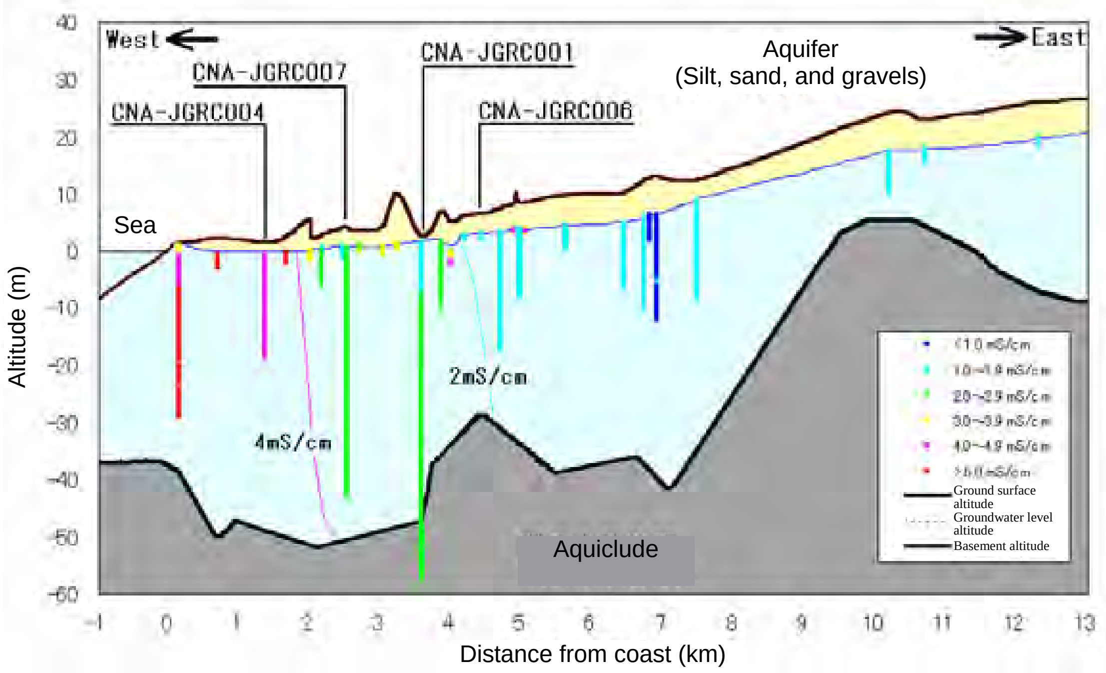
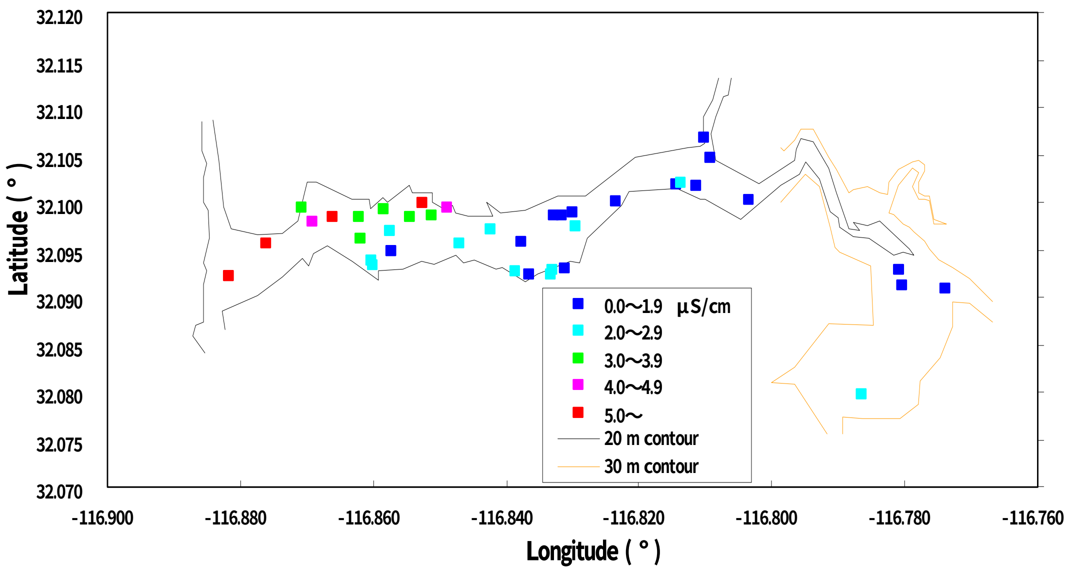


Figure 4.4.32 Electric Conductivity Distribution of Groundwater (Plane)



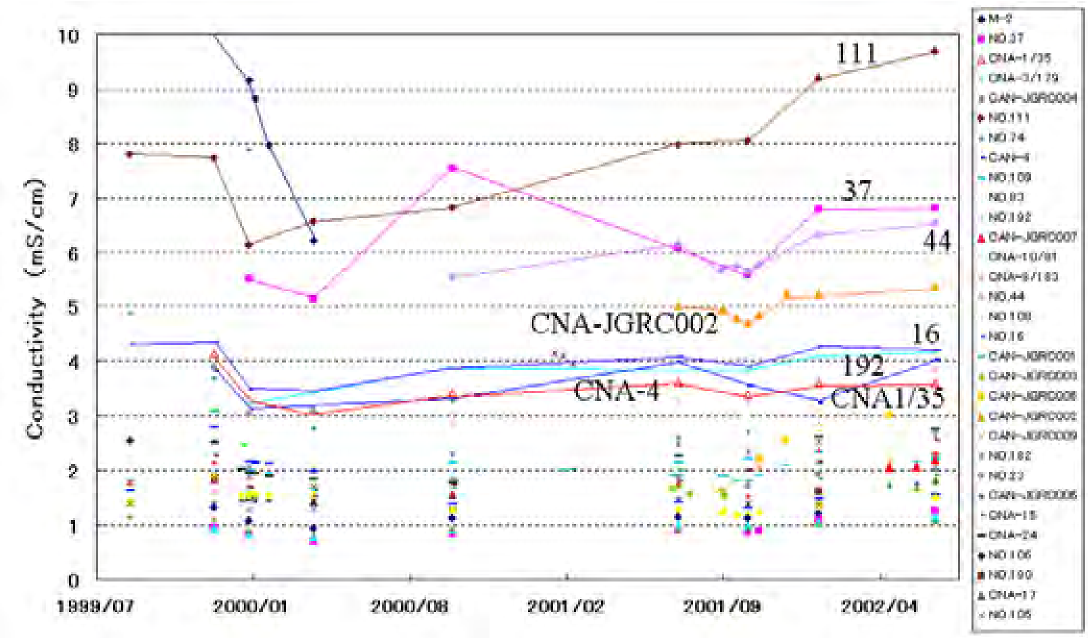
The electric conductivity of groundwater reaches up to 7.5 mS/cm near the coast. As the distance from the coast increases and the groundwater level rises, the electric conductivity gradually decreases. Within 4 km from the coast, the electric conductivity often exceeds 2 mS/cm, indicating that the groundwater is partially salinized. From the downstream to midstream catchment area, the electric conductivity of groundwater is not symmetric between the right and left banks of the valley. On the right bank (northern side) of the valley, the electric conductivity is comparatively as high as 3 to 4 mS/cm from a well located on the coast up to one about 4 km inland from the coast. On the left bank (southern side) of the valley, however, the electric conductivity is 2 mS/cm or less for a well more than

2 km from the coast.

In a frequently pumped well, stirring seems to make the water homogenous. In a large-diameter well, convection tends to make the water homogenous. For most wells in this region, the water quality seems to be homogenous.

Groundwater of the lowest electric conductivity is at the junction of the Guadalupe River and La Zorra River. The electric conductivity is about 0.8 to 0.9 mS/cm.

Figure 4.4.33 Electric Conductivity of Groundwater Over Time



- Groundwater temperature

The groundwater temperature at 7 or 8 km from the coast is 40°C or more. The maximum measured temperature is about 50°C. The correlations between rainfall and water temperature show that the water and electric conductivity tend to fall when the groundwater level rises in the rainy season and rise when the groundwater level falls.

The hot groundwater may be explained as follows. The groundwater originated from surface water that permeated into the hot basement, heated there, and welled to the aquifer again. This is indicated by the results of water analysis on major components revealing that the hot groundwater is not very different from the cold groundwater. Changes of the water temperature and electric conductivity may be attributable to charge of the cold groundwater rather than supply of the hot groundwater.

- Groundwater component analysis

As part of this survey, the water from about 20 wells was analyzed four times in 1999 to 2002 for electric conductivity, pH, total dissolved solids, amount of dissolved oxygen, amounts of major dissolved ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, and HCO_3^-), alkali degree, hardness, total number of coliform groups, and number of coprophilic coliform groups.

Figure 4.4.34 shows the correlations of Cl^- and Ca^{2+} concentrations in groundwater analyzed in 1999 to 2001. The straight line in the figure indicates the Cl^- to Ca^{2+} concentration ratio in general seawater. Compared with the seawater, the groundwater in this region contains more Ca^{2+}. As mentioned before, the electric conductivity of groundwater rises as the distance from the coast decreases. This may be an indication that the groundwater in the downstream catchment area is more salinized. The cation exchange reaction shown below may have occurred between the salinized groundwater and the aquifer components and increased Ca^{2+}.

$CaX_2+2Na^+ \longrightarrow 2NaX+Ca^{2+}$ (X: Ion exchanger in aquifer)

The red data in the figure is from the hot groundwater 7 or 8 km from the coast. Compared with the cold groundwater, the hot groundwater does not show peculiar water quality.

Figure 4.4.34 Correlations of Cl^- and Ca^{2+} Concentrations in Groundwater

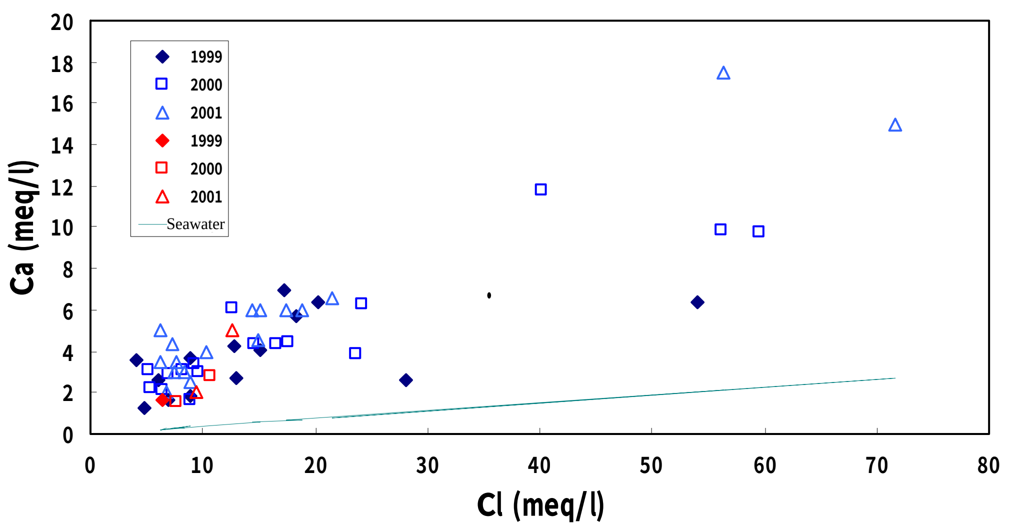
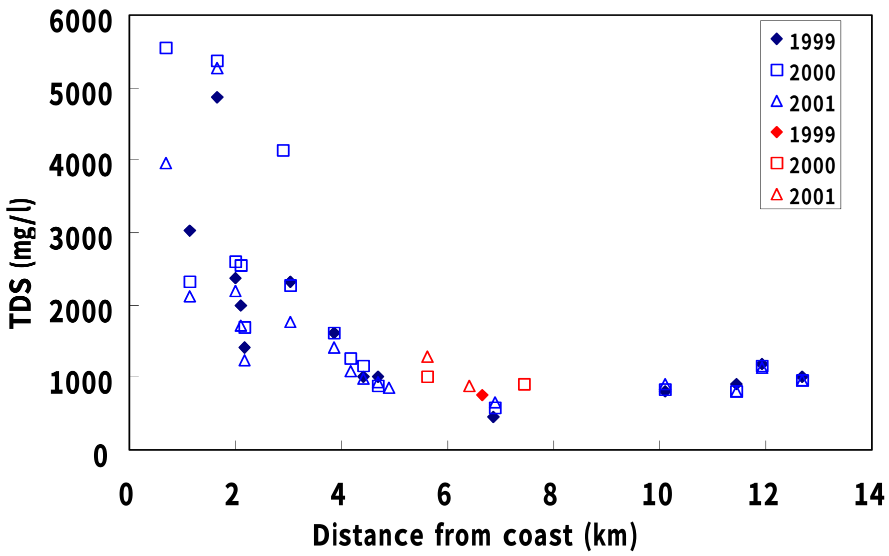


Figure 4.4.35 shows the relationship between the distance from the coast and the total dissolved solids (TDS). TDS increases as the distance from the coast decreases but is the lowest at about 7 km from the coast. A similar tendency can also be pointed out for the electric conductivity and the concentration of each major dissolved ion. The point about 7 km from the coast falls at the junction of the Guadalupe River and La Zorra River. The groundwater of low TDS flowing from the catchment area of La Zorra River may be locally reducing the electric conductivity of the aquifer about 7 km from the coast.

Figure 4.4.35 Relationship between Distance from the Coast and Total Dissolved Solids



- Discussion of factors for groundwater salinization

The salinization of groundwater within several kilometers from the coast is partially attributable to current groundwater pumping. Excess pumping may also be a factor. CESPE installed drinking wells at the downstream of this region in 1960 to 1965 and started sending water to Tijuana about 100 km to the north. Four wells were installed within 3 km from the coast and about 4 million m^3, nearly equal to the current yield, was pumped annually. Of these wells, two within 2 km from the coast showed groundwater salinization. Therefore, all the wells including the two upstream wells not salinized were abandoned. Toward 1972, the water source was transferred to the current position (about 7 km from the coast). In other words, the saltwater that flowed into the area in the 1960s may still exist with high salinity in the downstream catchment area. Even in the same downstream catchment area, the wells on the left bank are still used for drinking although their yields are relatively small. The water is not salinized and is comparatively good.

Compared with groundwater on the left bank, that on the right bank has high electric conductivity and more dissolved substances. The causes are not known in detail but may be as follows:

1) During pumping, the groundwater level in a well becomes lower than the seawater level. This causes local salt water infiltration and raises the electric conductivity.
2) The mountains on the right bank show landslide topography. This is probably because groundwater that has gained large amounts of dissolved substances while permeating through crushed siltstones or basalt from the mountains is added to the aquifer. This hypothesis originates from the fact that the groundwater in boreholes in the mountains has high electric conductivity.

4.4.5 Hydraulic analysis

(1) Water balance analysis

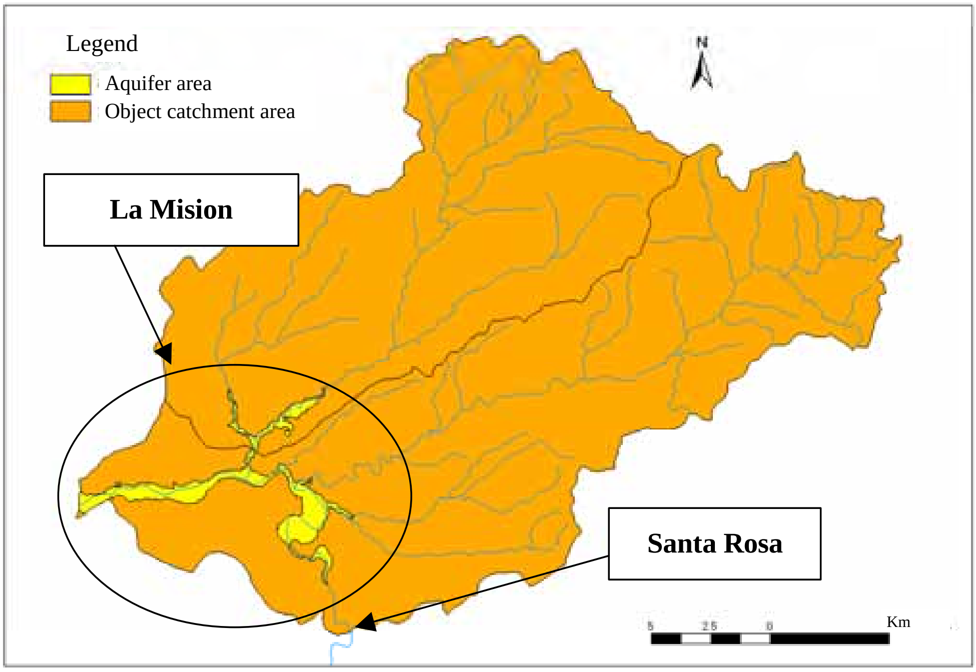
(a) Analytical flow

With the series tank model, hydraulic analysis was conducted as follows:

1) Categorize the basic data.
2) Study the approximate groundwater charge.
3) Study the approximate water balance using a tank model of the entire catchment area.
4) Create a series tank model.
5) Analyze the water balance using the series tank model.

The object of analysis is a range of about 463 km^2 from La Mision to Santa Rosa in the catchment area of the Guadalupe River (Figure 4.4.36). Within this range, the major aquifer distribution area is about 11 km^2.

Figure 4.4.36 Object Range of Hydraulic Analysis



(b) Preparation of analytical conditions

- Catchment area precipitation

The catchment area precipitation for water balance analysis was calculated using the Thiessen method. La Mision, Santa Rosa, El Porvenir, and Belen were adopted for Thiessen segmentation, the results of which are shown in Figure 4.4.37. Figure 4.4.38 shows the calculated mean annual precipitation in the entire catchment area. For reference, the figure also gives the annual precipitation data at El Porvenir and Santa Rosa that were used for Thiessen segmentation. If not available from a precipitation observation point used for segmentation, calculation data is compensated for according to correlations between precipitation observation points studied previously.

Figure 4.4.37 Thiessen Segmentation

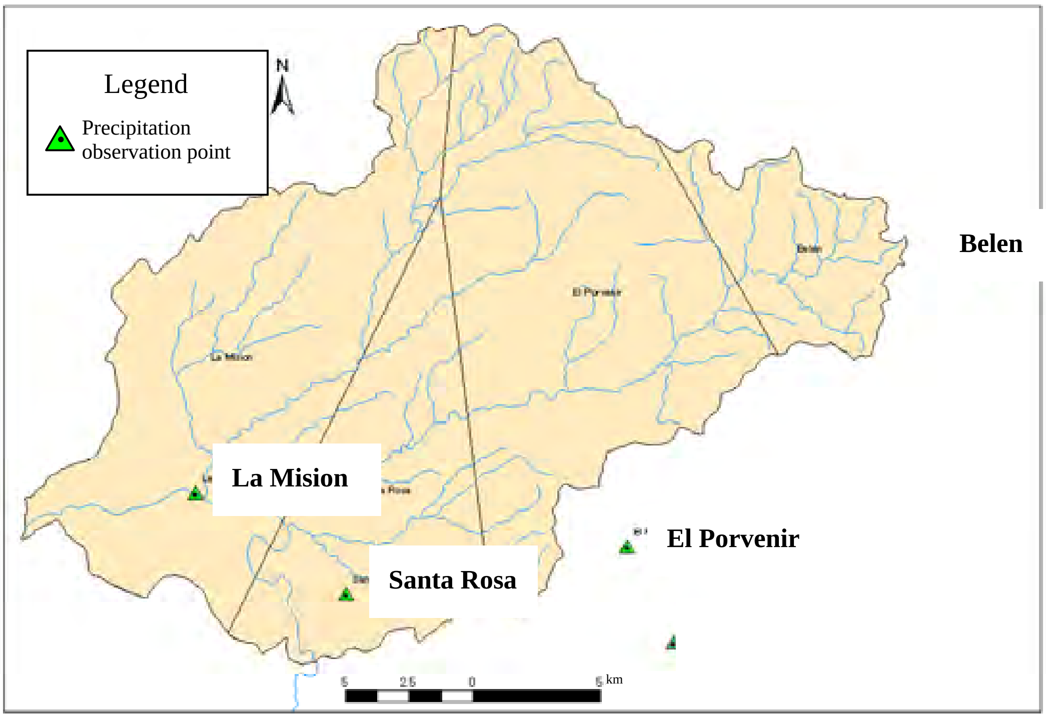
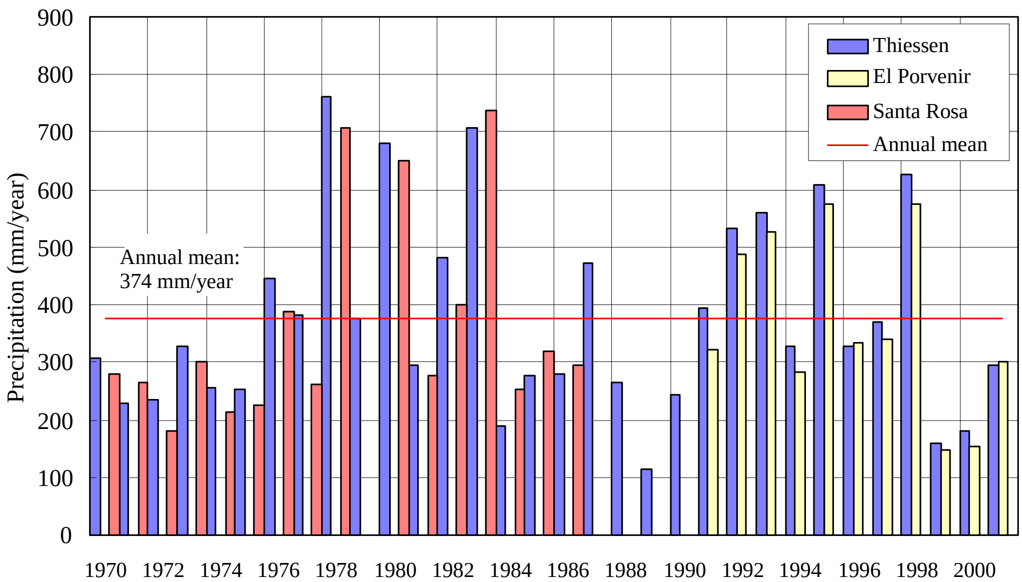


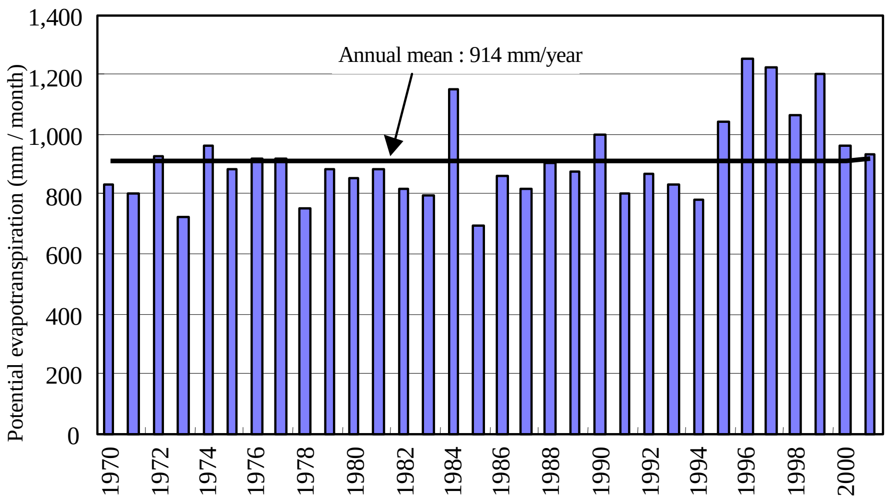
Figure 4.4.38 Transition of Catchment Area Precipitation Used for Hydraulic Analysis



- Evapotranspiration

For evapotranspiration, observation data at Santa Rosa was adopted because it was the only point in the catchment area where gage evaporation had been observed over a long time. This observation data was multiplied by a prescribed coefficient to determine potential evapotranspiration. The coefficient was set to 0.6. Figure 4.4.39 shows the annual transition of calculated potential evapotranspiration. A period lacking in data was appropriately compensated for from correlations between observation points obtained by studying meteorological data.

Figure 4.4.39 Transition of Potential Evapotranspiration Used for Hydraulic Analysis



- Groundwater yield

For water balance analysis, groundwater yield data was obtained by assuming the transition of annual yield as shown in Figure 4.4.20. To determine the yield by month, the annual yield was apportioned to months by considering the pumping patterns, although yields such as those from drinking wells were already known. For a daily yield, the monthly yield was divided by the number of days in the month. Figures 4.4.40 and 4.4.41 show calculated annual and monthly yields.

Figure 4.4.40 Transition of Annual Yield Used for Analysis

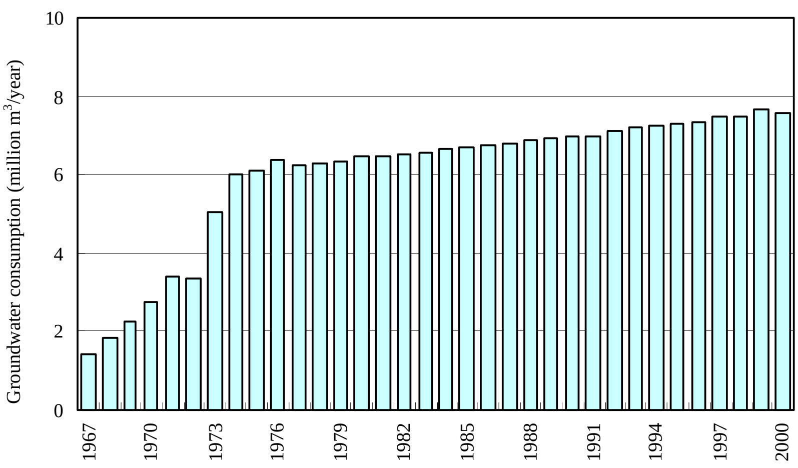
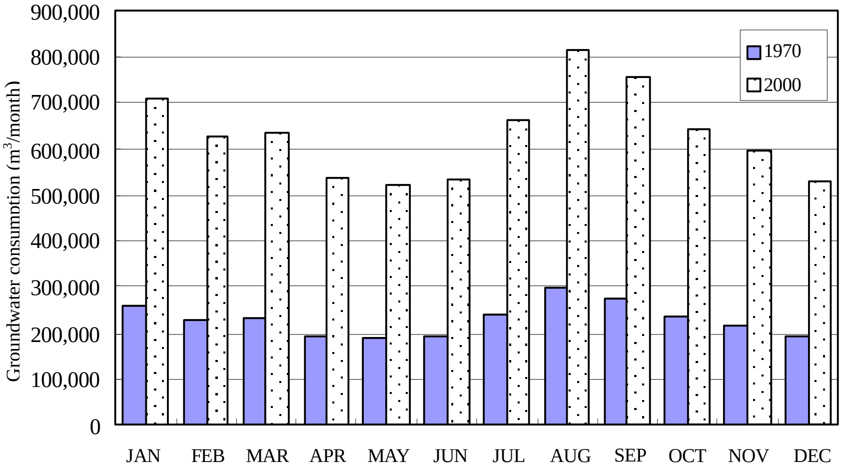


Figure 4.4.41 Monthly Yield Used for Analysis



- Groundwater level

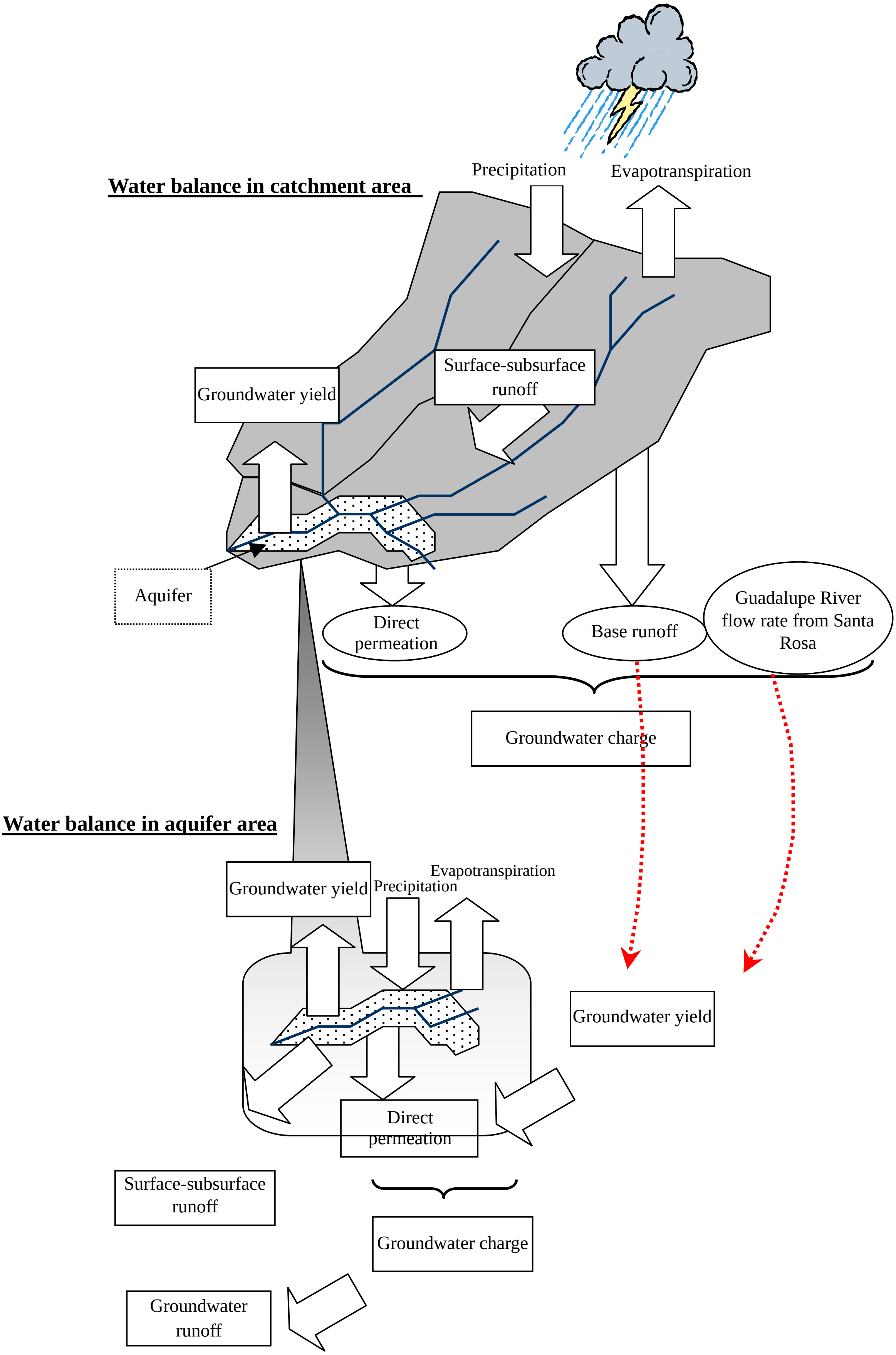
For the groundwater level, observation data since 1972 was used. The groundwater level repeatedly rises and falls locally depending on rainfall, but is gradually falling globally with the growth of groundwater consumption. The tendency of the groundwater level to fall has been particularly obvious since 1999 when the precipitation was comparatively small. The groundwater yield in excess of the groundwater charge is assumed to create the negative water balance.

- Water circulation mechanism

Figure 4.4.42 shows the water circulation mechanism assumed in this region. The object catchment area of analysis (about 463 km^2) is divided into an aquifer distribution area (aquifer area: 10.67 km^2) and another area (non-aquifer area: 453 km^2).

In the non-aquifer area, the balance of precipitation after evapotranspiration is the surface-subsurface and base runoff. Of the runoff, the base runoff becomes groundwater charge to the downstream aquifer area. Part of the rainfall in the aquifer area directly permeates into the aquifer. In a normal year, all water from the Guadalupe River also permeates into the ground after passing Santa Rosa to become part of the groundwater charge.

Figure 4.4.42 Water Circulation Mechanism



- Groundwater charge rate

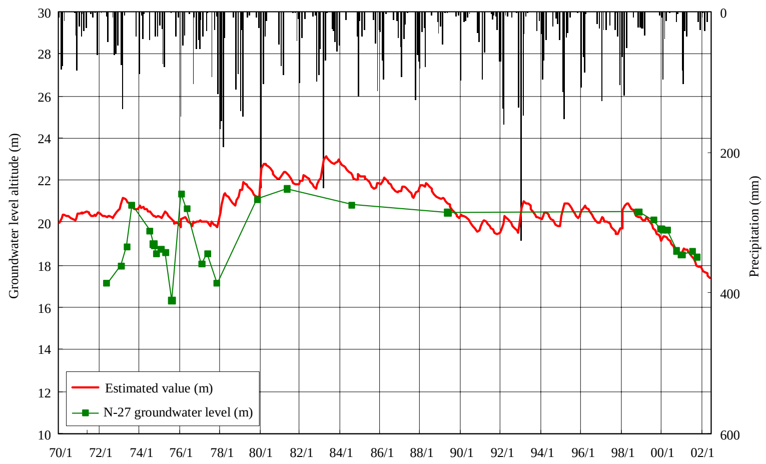
In this region, about 7 million m^3 of groundwater is now pumped annually. The groundwater level tends to fall these days but is not showing a drastic or tremendous drop. Therefore, the groundwater charge in this area seems to be about equal to or less than the groundwater yield.

Rainfall in the entire object catchment area is assumed to produce base runoff (groundwater charge) at a certain rate (groundwater charge rate) for the total amount corresponding to the groundwater yield. Therefore, base runoff (groundwater charge) not conflicting with this assumption is assumed. The base runoff (groundwater charge) estimation procedure is as follows:

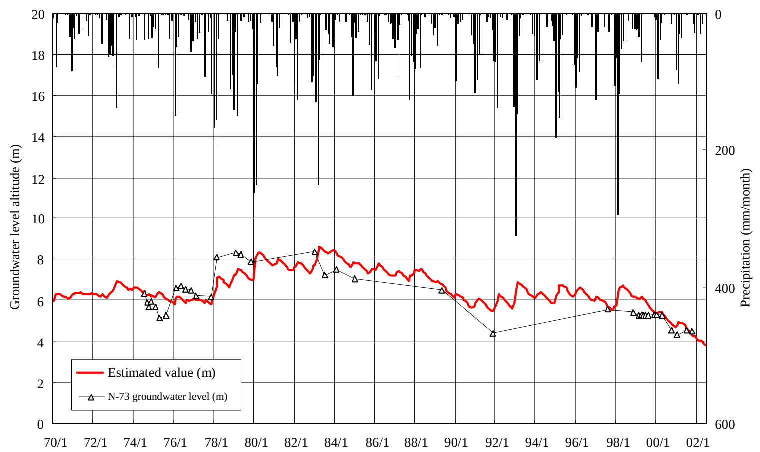
1)Assume that α% (groundwater charge rate) of the monthly precipitation in the object catchment area becomes base runoff.
2)Multiply the monthly precipitation in the object catchment area in the survey period by α to determine the monthly base runoff.
3)Add the direct monthly permeation (assumed value) in the aquifer area to the monthly base runoff to determine the monthly groundwater charge.
4)Subtract the monthly yield from the monthly groundwater charge to determine the monthly fluctuation of the groundwater reservoir.
5)Accumulate the monthly fluctuations of groundwater reservoir to determine the transition of groundwater storage.
6)Divide the groundwater storage by the effective porosity (assumed value) to determine the groundwater level with the passage of time.
7)Compare the fluctuation of the calculated groundwater level with that of the measured groundwater level in the study period to determine α by trial and error for a good match.

Figure 4.4.43 compares the calculated and measured groundwater levels. As a result of study, the calculated value was found to suitably match the measured value when α is about 3.5%. From this, the base flow rate in the object catchment area is estimated to be about 3 or 4%. Figure 4.4.44 shows the groundwater charge (base runoff) estimated by the above study.

Figure 4.4.43 Comparison of Calculated and Measured Groundwater Levels in Base Runoff Study

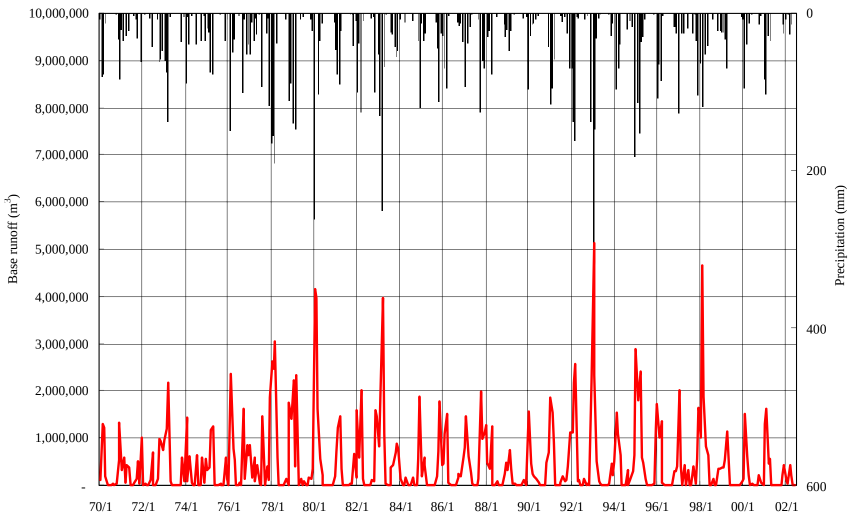


(N-27 point–Upstream of aquifer area–; α = 3.5%, effective porosity = 0.5)



(N-73 point–Downstream of aquifer area–; α = 3.5%, effective porosity = 0.6)

Figure 4.4.44 Estimated Base Runoff

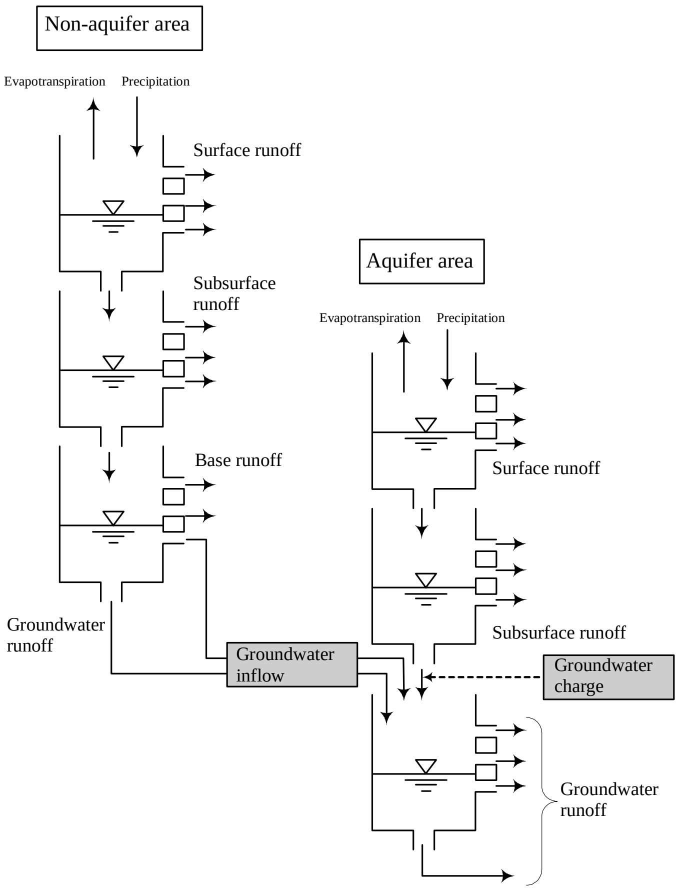


(c) Estimation of groundwater charge

The groundwater charge into the aquifer area was estimated using a tank model. By assuming the non-aquifer area in La Mision as a tank, the base runoff from the tank and the groundwater runoff were assumed to be groundwater charge into the aquifer area. The tank model had one row and three stages as shown in Figure 4.4.45. For calculation, data from 1970 until 2001 was used. Various coefficients of the tank model were set to satisfy the following conditions:

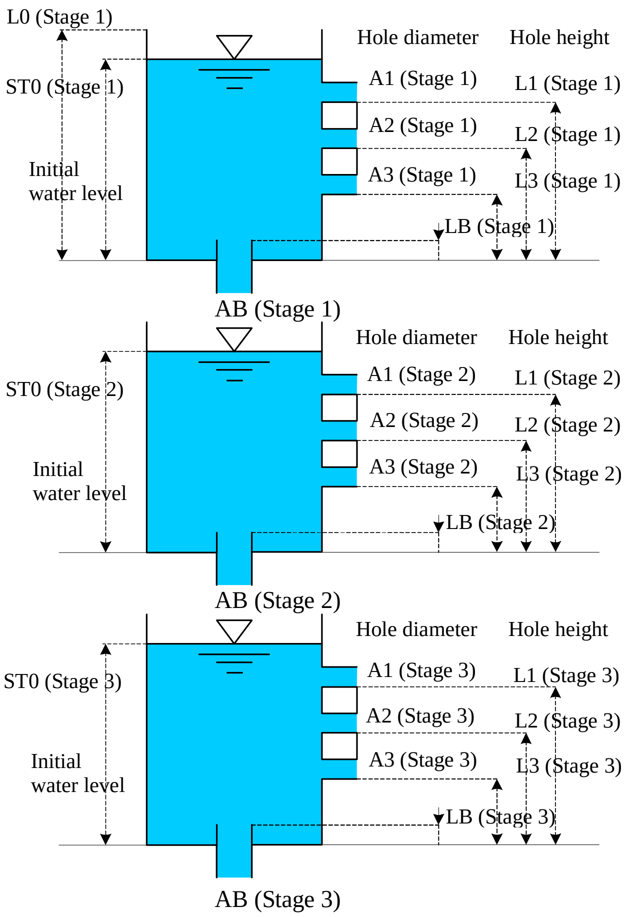
1) The base runoff shall be about 3 or 4% of the precipitation.
2) The surface runoff shall be about 10% of the precipitation.

Figure 4.4.45 Conceptual Drawing of the Tank Model



To satisfy the above conditions, the coefficients of the tank model were varied. Figure 4.4.46 shows the final coefficients determined. Figure 4.4.47 shows the groundwater charge based on the tank model, using the base runoff values studied in the previous section. Table 4.4.8 gives the water balance calculated on the basis of this model.

Figure 4.4.46 Coefficients of the Non-aquifer Tank Model



Stage 1	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	0
L0	-	300
A1,L1	0	200
A2,L2	0	100
A3,L3	0.0012	0
AB,LB	0.00084	0

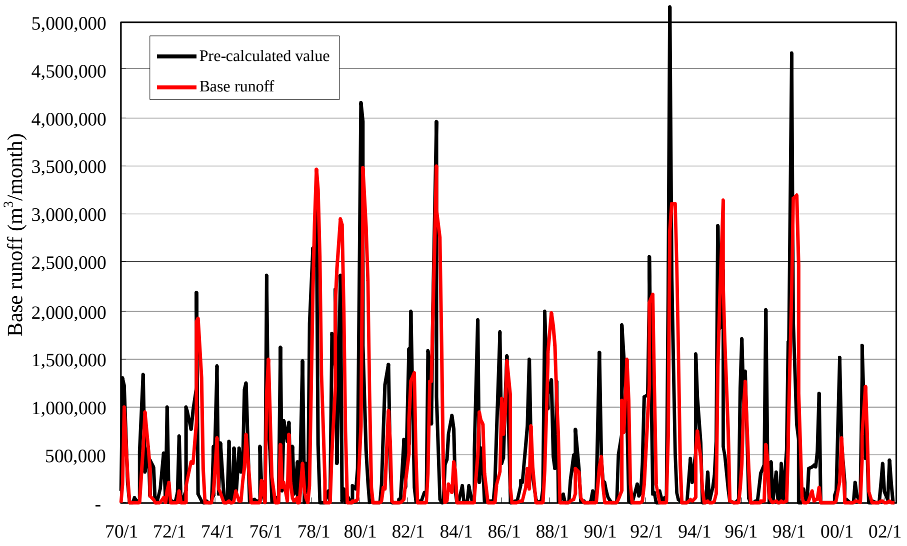
Stage 2	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	0	30
AB,LB	1	0

Stage 3	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	0
A1,L1	0	10
A2,L2	0	5
A3,L3	0.9	0
AB,LB	0	0

Table 4.4.8 Results of Water Balance Calculations (Unit: 1,000m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/ Subsurface Runoff	Groundwater Charge	Breakdown of Groundwater Charge		Storage
					Base runoff	Groundwater runoff	
Mean in 1970 to 1979	161,358 (356)	139,345 (308)	16,112 (36)	5,306 (12)	5,306 (12)	0 (0)	0 (0)
Mean in 1980 to 1989	170,378 (376)	142,524 (315)	22,402 (49)	6,047 (13)	6,047 (13)	0 (0)	0 (0)
Mean in 1990 to 2001	174,796 (386)	153,923 (340)	15,498 (34)	5,375 (12)	5,375 (12)	0 (0)	0 (0)
Annual mean (in mm)	169,216 (374)	145,805 (322)	17,847 (39)	5,563 (12)	5,563 (12)	0 (0)	0 (0)

Figure 4.4.47 Tank Model Calculation Results



(d) Water balance in the aquifer area

By using the non-aquifer base runoff and groundwater runoff (groundwater charge to the aquifer area), the water balance in the aquifer area was analyzed using a tank model. Figure 4.4.45 shows the structure of the tank model on the right. The base runoff and groundwater runoff in the non-aquifer area calculated using the tank model were directly input to Stage 3 of the aquifer tank model as groundwater charge, and the groundwater yield was output from Stage 3. In this calculation, the model is verified by checking consistency with the measured groundwater level observation data.

The calculation was made every day from January 1, 1970 to June 30, 2002. Figure 4.4.48 compares the calculated and measured groundwater levels. The groundwater levels calculated using the tank model approximately matched the measured groundwater levels. Figure 4.4.49 shows the coefficients of the tank model used for calculation. Table 4.4.9 gives the calculated water balance in the aquifer area.

Figure 4.4.48 Comparison of Calculated and Measured Groundwater Levels

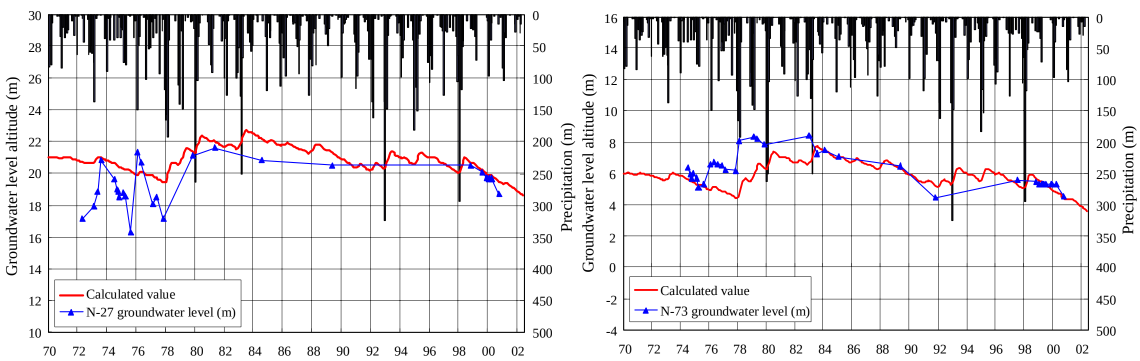
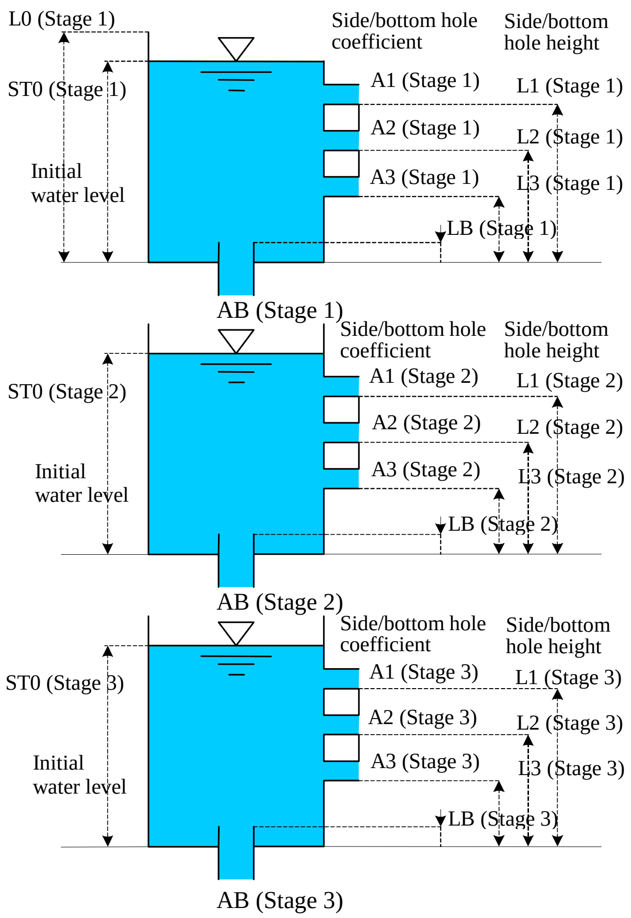


Figure 4.4.49 Coefficients of the Aquifer Tank Model



Stage 1	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	0
L0	-	50
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.12	0

Stage 2	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	0.00000001	30
AB,LB	0.0014	0

Stage 3	Side/bottom hole coefficient A	Side/bottom hole height L
ST0	-	3000
A1,L1	0.000001	3000
A2,L2	0.0000001	500
A3,L3	0.00000001	400
AB,LB	0.000001	400

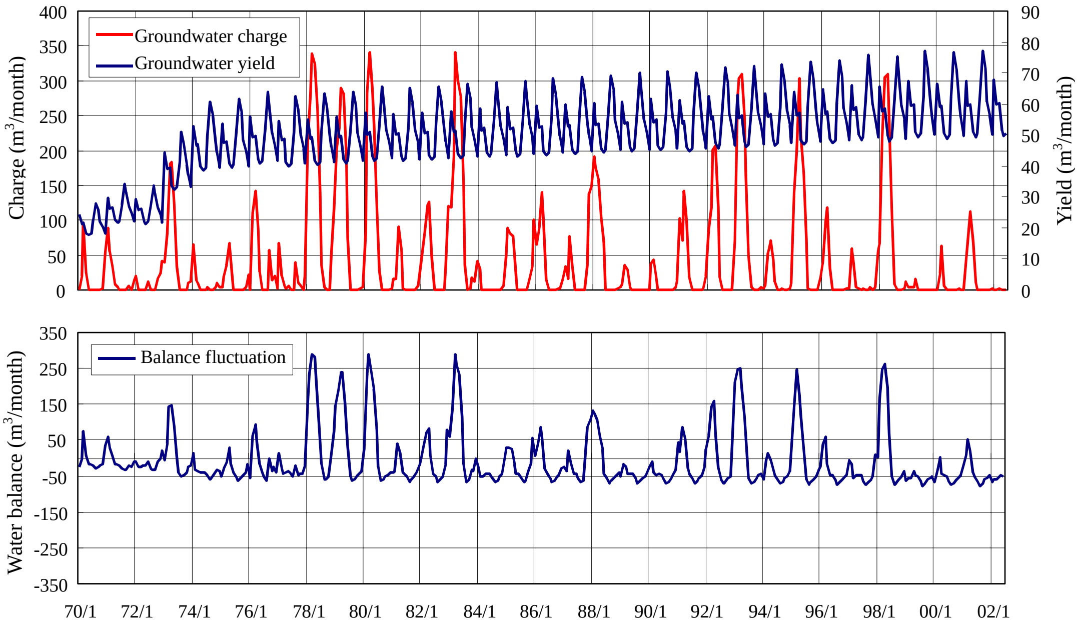
Table 4.4.9 Results of Aquifer-area Water Balance Calculations Using the Tank Model

(Catchment area size: 10.67 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/ Subsurface Runoff	Groundwater Charge	Base Runoff	Groundwater Runoff	Storage
Mean in 1970 to 1979	3,801 (356)	3,269 (306)	314 (29)	203 (19)	1 (0)	9 (1)	0 (0)
Mean in 1980 to 1989	4,013 (376)	3,343 (313)	458 (43)	227 (21)	5 (0)	13 (1)	0 (0)
Mean in 1990 to 2001	4,117 (386)	3,510 (329)	419 (39)	189 (18)	1 (0)	8 (1)	0 (0)
Annual mean (in mm)	3,986 (374)	3,382 (317)	398 (37)	206 (19)	2 (0)	10 (1)	0 (0)

Figure 4.4.50 shows the fluctuation of the calculated water balance. In this region, the water balance becomes positive in a year of heavy rainfall and groundwater charge, but negative in a year of low precipitation. The water balance thus fluctuates according to the rainfall.

Figure 4.4.50 Water Balance in the Aquifer Area Calculated Using the Tank Model



(e) Creation of the series tank model

The aquifer area in La Mision was divided into six sub-catchment areas (blocks) and a vertical permeation tank and lateral flow tank were set for each block. Then, the lateral flow tanks of the block were linked to each other to create a series tank model for more detailed analysis of the water balance.

The aquifer area was divided into blocks by catchment areas of small rivers flowing into La Mision. For forecast calculation after the construction of a subsurface dam, the area was also divided at the upstream and downstream of the subsurface dam construction site. Figure 4.4.51 shows the block divisions of the aquifer area used to create the series tank model.

Figure 4.4.52 shows the structure of the created series tank model. Each block is expressed as a tank consisting of one row and three stages. The Stage-3 tanks (lateral flow tanks) of the blocks were linked along the actual groundwater flow channel. In the figure, the arrows indicate groundwater charge (annual mean) from around the aquifer area and also groundwater yield (data of 2000) from the local wells to the lateral flow tank of each block. The lateral flow tank of Block 1 located at the position furthest downstream was assumed to be adjacent to the seawater surface. Therefore, the seawater surface altitude is always set to 0 m.

Figure 4.4.51 Block Divisions of the Series Tank Model

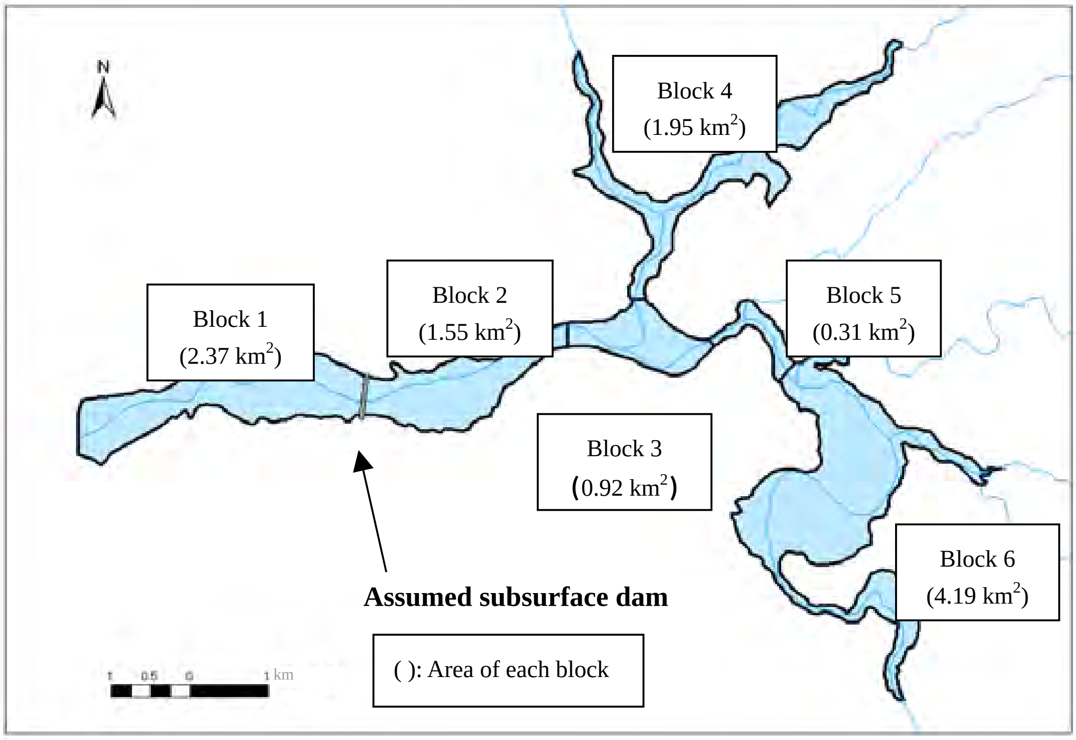
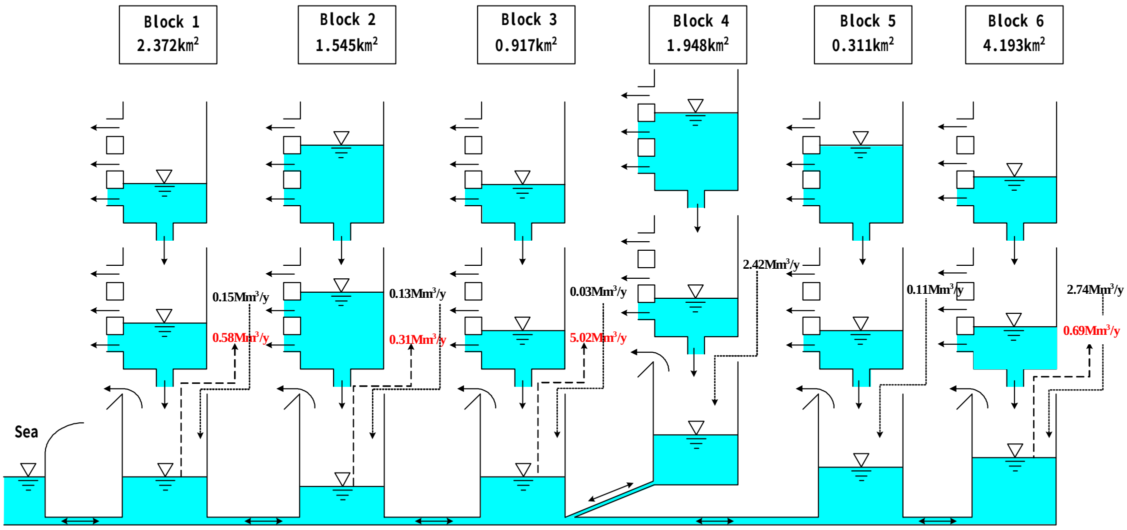


Figure 4.4.52 Structure of the Series Tank Model



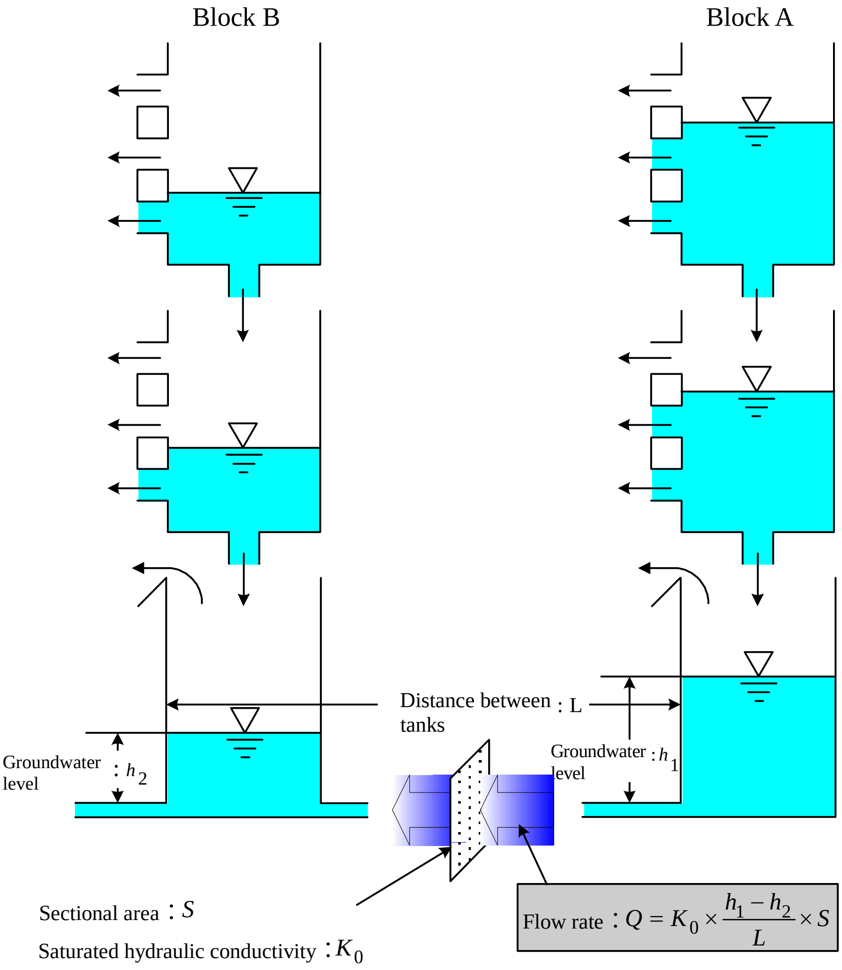
The groundwater flow between the lateral flow tanks was estimated according to Darcy's Law. Figure 4.4.53 shows the concept of calculating a groundwater flow rate between lateral flow tanks. The saturated hydraulic conductivity K_0 used for this calculation is calculated as follows:

$$K_0 = \left(\frac{K_A + K_B}{2} \right)$$

K_A : Saturated hydraulic conductivity of Block A

K_B : Saturated hydraulic conductivity of Block B

Figure 4.4.53 Concept of Calculating Groundwater Flow Rate between Lateral Flow Tanks



The groundwater charge in all catchment areas calculated in “(c) Estimation of groundwater charge” was allotted proportionally according to the area ratio of the catchment area in each block to determine the ground charge to each block. Figure 4.4.5.4 shows the allotment ratios.

According to the positions of the pumped wells, the total yield from the blocks in 2000 was calculated to determine the yield from each block and the ratio to the total yield from all blocks. Based on these ratios, the annual total yield studied in the previous section was proportionally apportioned to the blocks. Figure 4.4.55 shows the annual groundwater yield from each block in 2000. In this region, groundwater is pumped in Block 3 for 76% of the total yield. In Blocks 1, 2, and 6, about 0.3 to 0.6 million tons of groundwater is pumped. No groundwater is pumped in Block 4 or 5.

Figure 4.4.54 Catchment Area in Each Block

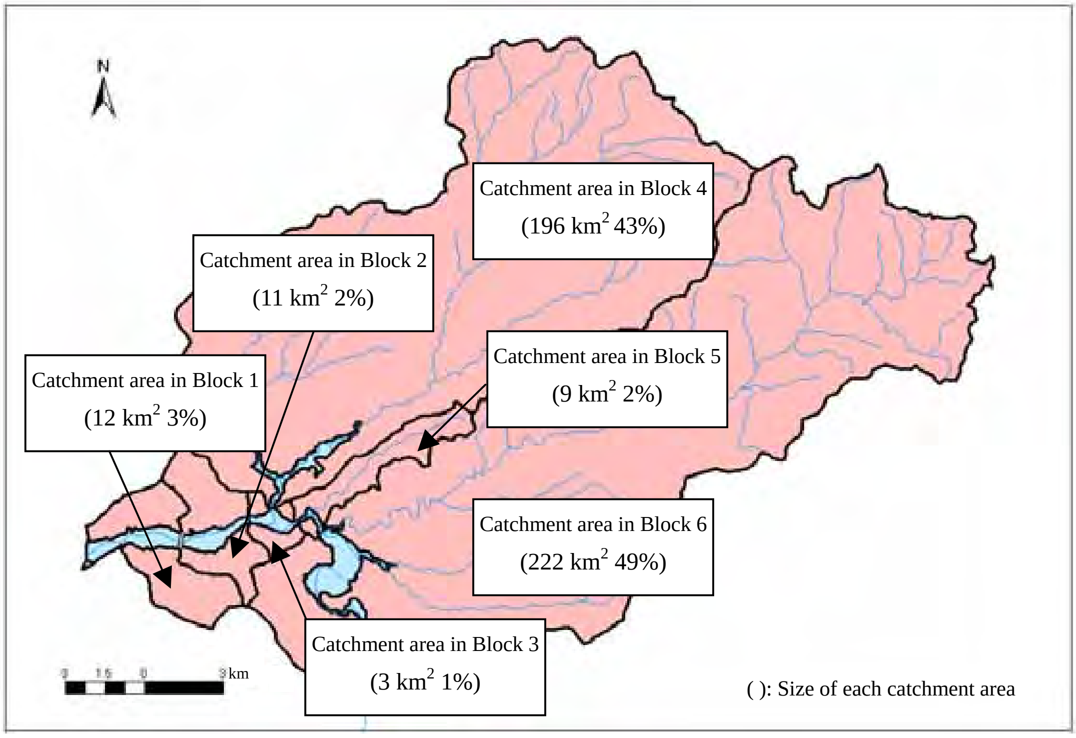
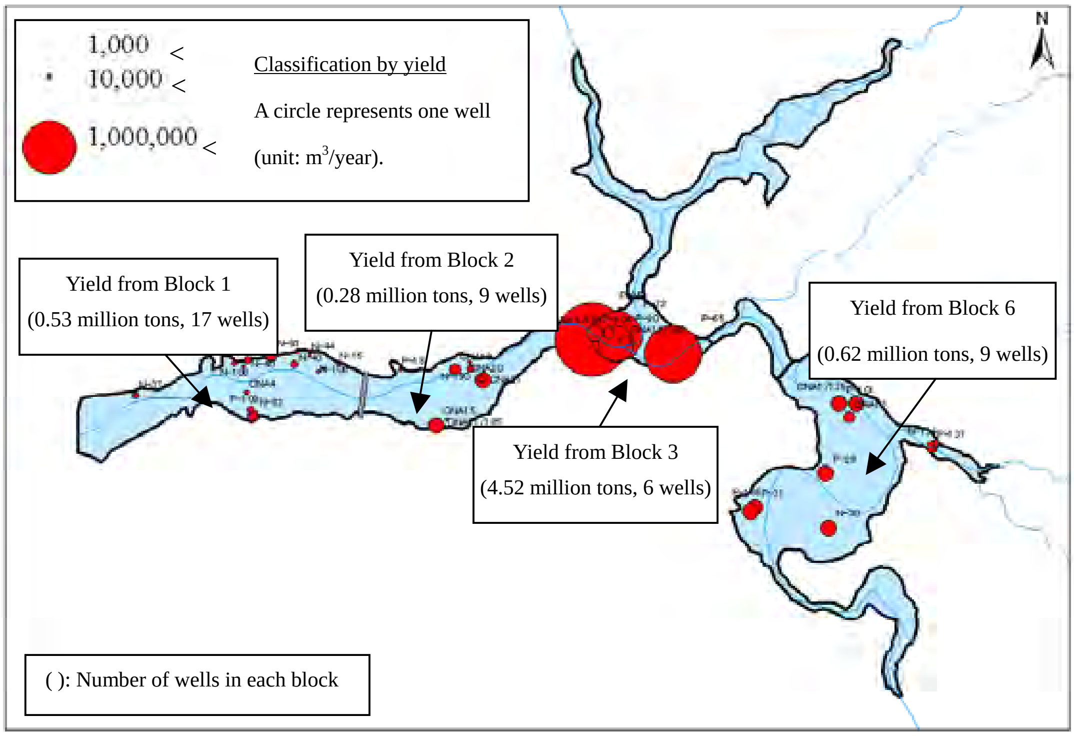


Figure 4.4.55 Groundwater Yield from Each Block



(f) Series tank model calculation results

The series tank model was calculated using data on the groundwater charge from the non-aquifer area and the groundwater yield in the aquifer area calculated in the previous sections. For precipitation, the data at the observation point in La Mision was used. The calculation was performed in units of a day from January 1970 to June 2002. To verify the model, the calculated and measured groundwater levels in each block were compared. By varying the parameters, the calculation was repeated until the measured and calculated water levels matched. Figure 4.4.56 shows the results of calculation with the final determined model. Tables 4.4.10 and 4.4.11 list the parameters used for the calculation.

Figure 4.4.56 Series Tank Model Calculation Results

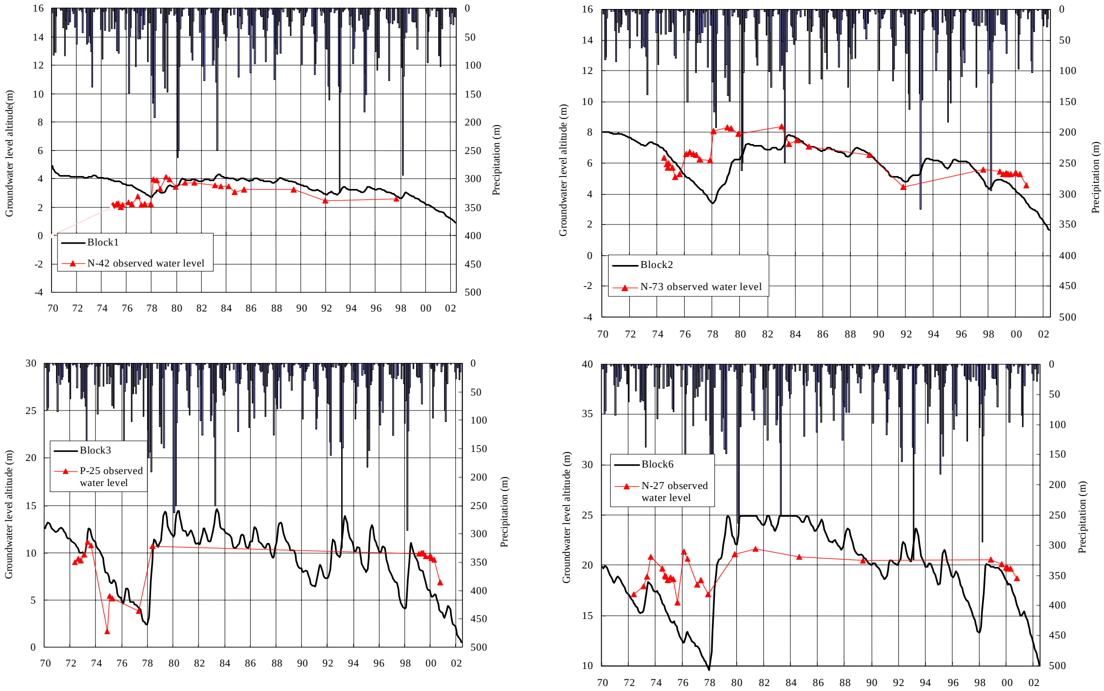
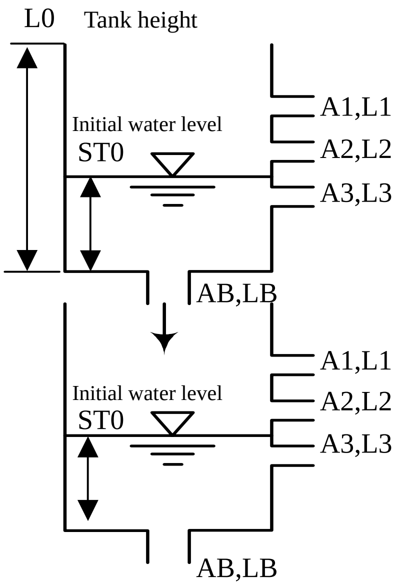


Table 4.4.10 Parameters Used for Series Tank Model Calculation

Block	Adjacent Tank	Tank Bottom Altitude (m)	Saturated Hydraulic Conductivity (cm/sec)	Effective Porosity	Distance from Adjacent Tank (m)	Sectional Area (m^2)
Block 1	Sea	-30.0	5.0×10^{-2}	0.3	2,000	5,000
Block 2	Block 1	-30.0	5.0×10^{-2}	0.3	3,000	33,000
Block 3	Block 2	-20.0	5.0×10^{-2}	0.2	1,500	14,000
Block 4	Block 3	-20.0	5.0×10^{-1}	0.2	500	9,000
Block 5	Block 3	-20.0	5.0×10^{-2}	0.2	100	6,000
Block 6	Block 5	15.0	5.0×10^{-2}	0.2	500	15,000

Table 4.4.11 Parameters of the Series Tank Model



Block 1		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Block 2		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Block 3		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Block 4		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Block 5		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Block 6		
Stage 1	Side/bottom hole coefficient	Side/bottom hole height
L0	-	50
ST0	-	0
A1,L1	0	50
A2,L2	0	40
A3,L3	0.00000001	30
AB,LB	0.15	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Stage 2	Side/bottom hole coefficient	Side/bottom hole height
ST0	-	0
A1,L1	0	100
A2,L2	0	50
A3,L3	1E-10	30
AB,LB	0.0011	0

Table 4.4.12 gives the water balance in each block calculated using the series tank model. Figure 4.4.57 shows the transition of the water balance in each block with the passage of time. The total (32-year) water balance in the calculation period was negative in all blocks except Block 1. In particular, Blocks 4 and 6 showed large negative values, indicating substantial groundwater supply to Block 3 that yields a great amount of groundwater.

Table 4.4.12 Water Balance in Each Block

Block 1 (2.372 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/Subsurface Runoff	Groundwater Charge	Groundwater Inflow from Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	977 (412)	831 (350)	92 (39)	49 (21)	146 (61)	431 (182)	178 (75)	107 (45)	457 (193)	-115 (-49)
Mean in 1980 to 1989	1,003 (423)	837 (353)	116 (49)	55 (23)	166 (70)	534 (225)	39 (16)	114 (48)	589 (248)	13 (5)
Mean in 1990 to 2001	1,060 (447)	875 (369)	138 (58)	46 (20)	148 (62)	386 (163)	0 (0)	73 (31)	646 (272)	-139 (-59)
Annual mean	1,016 (428)	850 (358)	117 (49)	50 (21)	153 (64)	446 (188)	68 (29)	96 (41)	569 (240)	-84 (-36)

Block 2 (1.545 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/ Subsurface Runoff	Groundwater Charge	Groundwater Inflow from Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	636 (412)	541 (350)	60 (39)	32 (21)	124 (80)	444 (287)	3 (2)	431 (279)	246 (159)	-80 (-52)
Mean in 1980 to 1989	653 (423)	546 (353)	76 (49)	36 (23)	142 (92)	664 (429)	0 (0)	534 (346)	317 (205)	-10 (-6)
Mean in 1990 to 2001	690 (447)	570 (369)	90 (58)	30 (20)	126 (82)	430 (278)	0 (0)	386 (250)	348 (225)	-147 (-95)
Annual mean	662 (428)	554 (358)	76 (49)	32 (21)	130 (84)	507 (328)	1 (1)	446 (289)	306 (198)	-83 (-54)

Block 3 (0.917 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/Subsurface Runoff	Groundwater Charge	Groundwater Inflow from Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	378 (412)	321 (350)	35 (39)	19 (21)	29 (32)	4,609 (5,026)	287 (313)	444 (484)	3,927 (4,283)	-1 (-1)
Mean in 1980 to 1989	388 (423)	324 (353)	45 (49)	21 (23)	33 (36)	6,039 (6,586)	436 (476)	664 (724)	5,060 (5,518)	-66 (-72)
Mean in 1990 to 2001	410 (447)	338 (369)	53 (58)	18 (20)	30 (32)	5,935 (6,472)	91 (99)	430 (469)	5,555 (6,058)	-94 (-103)
Annual mean	393 (428)	329 (358)	45 (49)	19 (21)	31 (34)	5,553 (6,055)	260 (284)	507 (553)	4,892 (5,334)	-56 (-61)

Block 4 (1.948 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/Subsurface Runoff	Groundwater Charge	Groundwater Inflow from Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	802 (412)	683 (350)	75 (39)	40 (21)	2,297 (1,179)	0 (0)	163 (84)	2,261 (1,161)	0 (0)	-87 (-45)
Mean in 1980 to 1989	824 (423)	688 (353)	96 (49)	45 (23)	2,618 (1,344)	0 (0)	417 (214)	2,401 (1,233)	0 (0)	-156 (-80)
Mean in 1990 to 2001	870 (447)	719 (369)	113 (58)	38 (20)	2,327 (1,194)	0 (0)	116 (59)	2,441 (1,253)	0 (0)	-192 (-99)
Annual mean	835 (428)	698 (358)	96 (49)	41 (21)	2,408 (1,236)	0 (0)	225 (115)	2,373 (1,218)	0 (0)	-148 (-76)

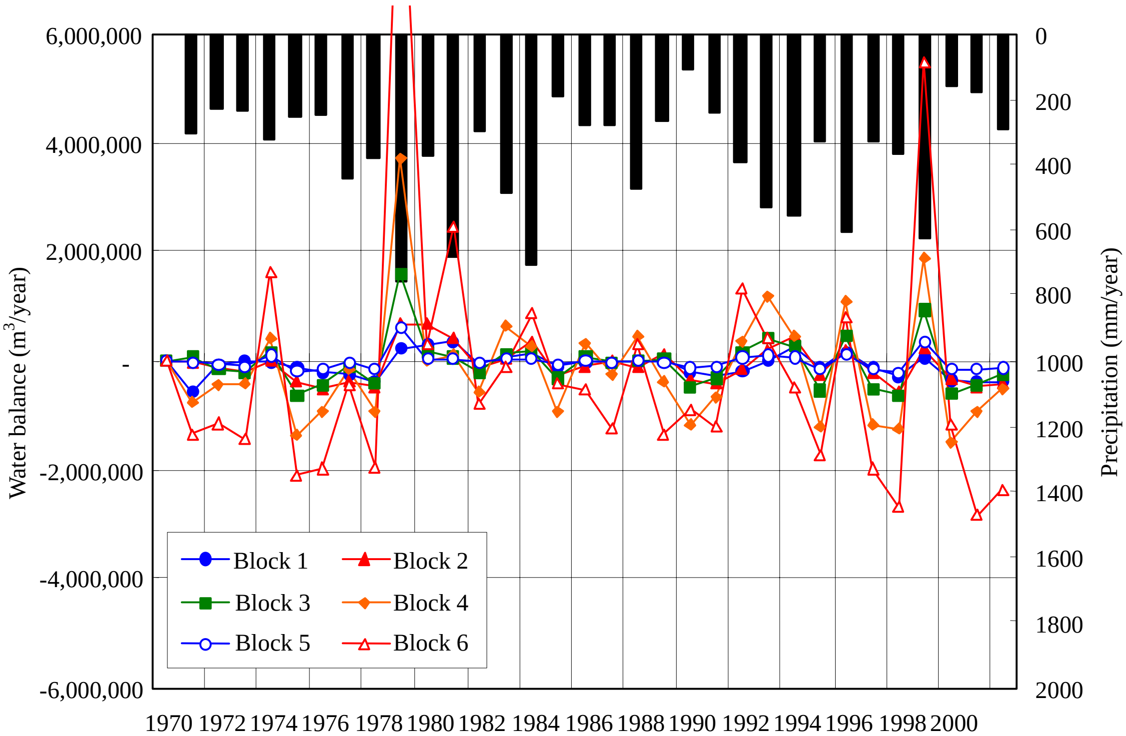
Block 5 (0.311 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Evapotranspiration	Surface/subsurface Runoff	Ground water Charge	Groundwater Inflow from Upstream Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	128 (412)	109 (350)	12 (39)	6 (21)	101 (325)	2,329 (7,488)	88 (281)	2,348 (7,548)	0 (0)	1 (5)
Mean in 1980 to 1989	132 (423)	110 (353)	15 (49)	7 (23)	115 (370)	3,978 (12,791)	481 (1,547)	3,638 (11,697)	0 (0)	-19 (-60)
Mean in 1990 to 2001	139 (447)	115 (369)	18 (58)	6 (20)	102 (329)	3,393 (10,910)	43 (137)	3,493 (11,232)	0 (0)	-34 (-110)
Annual mean	133 (428)	111 (358)	15 (49)	7 (21)	106 (341)	3,243 (10,428)	194 (622)	3,180 (10,226)	0 (0)	-18 (-58)

Block 6 (4.193 km^2) (Unit: 1,000 m^3/year, ( ): mm/year)

	Precipitation	Surface Water Inflow	Evapotranspiration	Surface/Subsurface runoff	Ground water Charge	Groundwater Inflow from Area	Groundwater Inflow from Upstream Tank	Base Runoff	Groundwater Runoff	Yield	Storage
Mean in 1970 to 1979	1,530 (365)	18,694 (4,458)	2,310 (551)	14,152 (3,375)	1,661 (396)	2,598 (620)	0 (0)	1,223 (292)	2,329 (555)	540 (129)	167 (40)
Mean in 1980 to 1989	1,673 (399)	60,169 (14,350)	3,579 (854)	44,899 (10,708)	14,600 (3,482)	2,961 (706)	0 (0)	13,056 (3,114)	3,978 (949)	695 (166)	169 (-40)
Mean in 1990 to 2001	1,665 (397)	10,357 (2,470)	3,272 (780)	7,474 (1,782)	1,998 (476)	2,632 (628)	0 (0)	1,013 (241)	3,393 (809)	764 (182)	-540 (-129)
Annual average	1,625 (388)	28,529 (6,804)	3,067 (732)	21,256 (5,069)	5,830 (1,390)	2,724 (650)	0 (0)	4,842 (1,155)	3,243 (773)	672 (160)	-203 (-48)

Figure 4.4.57 Transition of Water Balance in Each Block Over Time



According to the data in and after 1990, when more than 6 million m^3 of the groundwater is pumped in a year, the water balance becomes negative if the annual precipitation is less than 400 mm and positive if it is more than 400 mm. Since the annual precipitation in La Mision is about 300 to 400 mm, the water balance is estimated to always be about zero if such groundwater pumping continues in future. Because of water shortage since 1999, however, the water balance has also been negative.

(2) Groundwater flow and salt water infiltration analysis

Create a 3D numerical analytical model to reproduce groundwater flows and salt water infiltration behaviors and provide useful information for studying the effectiveness of the assumed subsurface dam.

(a) Analytical flow

Table 4.4.13 shows the hydraulic analysis flow.

Table 4.4.13 Flow of 3D Numerical Analysis

1. Creation of 3D numerical analytical model
Set (1) aquifer system, (2) boundary conditions, (3) hydraulic parameters (saturated hydraulic conductivity, dispersion coefficient, and effective porosity), (4) groundwater charge, and (5) yield to construct a 3D numerical analytical model using HST3D. For the groundwater charge, apply the results of water balance analysis using the tank model.

2. Verification and correction of the analytical model (Adjustment of hydraulic parameters)
To closely reproduce the groundwater shape and salinity distribution, repeat unstable calculations and adjust the aquifer thickness, conductivity coefficient, and other constants.

3. Future forecast calculation
Using the analytical model of adjusted hydraulic parameters, forecast the future with the subsurface dam to validate the dam.

(b) Construction of analytical model

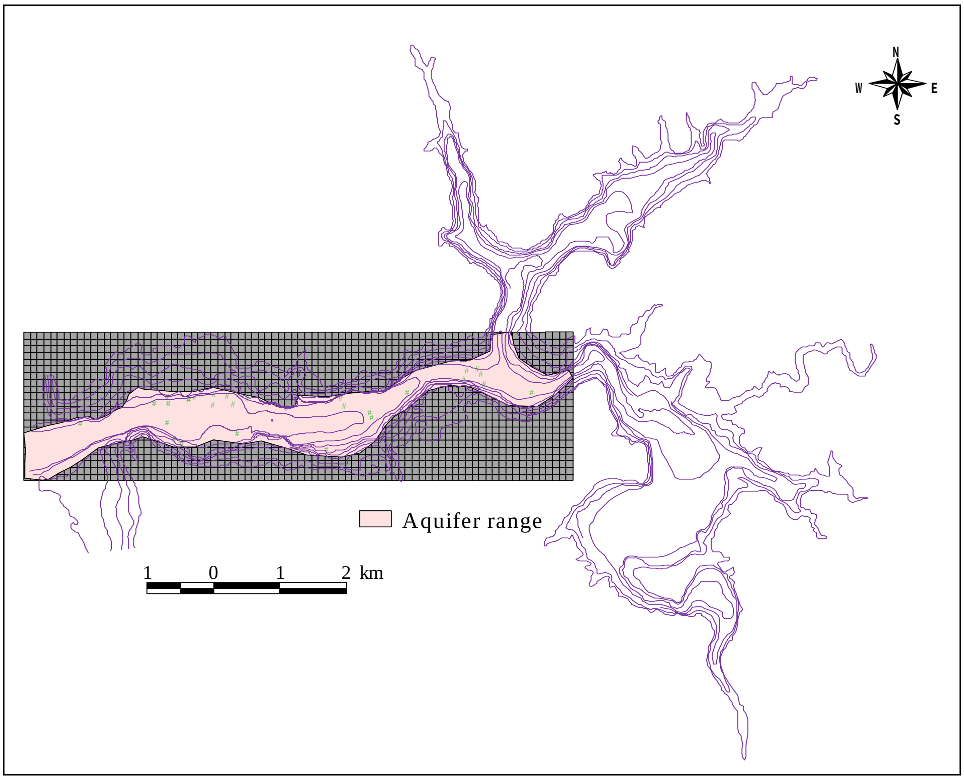
Using a 3D differential convective diffusion (HST3D), simulate the groundwater flows and their accompanying convective diffusion of heat or solute in three dimensions. This software can express the groundwater shape in more detail than the series tank model and also gives changes of the water quality. Therefore, the groundwater surface shape and the salt water infiltration with and without the subsurface dam are forecast in this analysis. This software is also used to forecast the rise of the reservoir level after subsurface dam construction and to design the drainage facilities. Since the calculation process takes a comparatively long time, however, the software is not suitable for long-term analysis.

For your reference, HST3D can be downloaded from an Internet site as free software. To use HST3D, however, Argus Open Numerical Environments (Argus One) sold by Argus is needed. Argus One is a program to preprocess and postprocess data and image displays for using software of a finite difference method such as HST3D or other finite element method.

1) Range of analysis

The range of analysis (Figure 4.4.58) is from Blocks 1 to 3 among the six blocks divided in the aforementioned series tank model. It is preferable to analyze the entire aquifer distribution area in La Mision. Extending the range of analysis makes it necessary to increase the calculation time or the analytical mesh width. Therefore, a model was constructed for the minimum necessary range for analysis.

Figure 4.4.58 Range of Analysis and Mesh Division



2) Grid division of the aquifer

The range of analysis was divided into square grids of 100 × 100 m on the plane. The grid size was set to 50 m in the east-west direction near the assumed dam axis and to 10 m directly upstream and downstream on the dam axis.

In the vertical direction, the range of analysis was divided into seven layers: Layer 1 (altitude: 10 to 2 m), Layer 2 (2 to –3 m), Layer 3 (-3 to -10 m), Layer 4 (-10 to -20 m), Layer 5 (-20 to -30 m), Layer 6 (-30 to -40 m), and Layer 7 (-40 to -50 m) from the top.

3) Boundary conditions

The west coast area was set as the known head boundary (EL. -0.5 m), the inflow sections of the main stream and tributary of the Guadalupe River into Block 3 as the known flow boundary, and other areas as non-flow boundaries.

4) Groundwater charge

Groundwater charge to the aquifer in the range of analysis can be classified into three: (1) groundwater permeation in the aquifer area attributable to rainfall, (2) groundwater charge from the surrounding area, and (3) groundwater charge from the blocks adjacent to Block 3. These groundwater charges were calculated by water balance analysis using the tank model and given as input data.

In addition, a model was set by considering the topographical shape to express the permeation of river water into the aquifer or the welling of groundwater to the surface.

5) Aquifer constants

The hydraulic conductivity of the aquifer was assumed to be 5×10^{-2} to 10^{-2} cm/sec and the effective porosity to be 0.1 to 0.3.

The dispersion coefficient was assumed to be 500 to 1000 m/day for the vertical direction and 100 to 200 m/day for the horizontal direction.

(c) Results of analytical calculations

1) Reproducing calculation

The groundwater levels and salinity concentrations in three years from July 1999 until June 2002 were reproduced using a model and compared with the actual observation results. Then the model parameters were adjusted. Figures 4.4.59 and 4.4.60 show the results. In Figure 4.4.60, the groundwater salinity is expressed as a ratio to the seawater salinity.

Figure 4.4.59 Results of Reproducing Calculation (Plane Distribution of Groundwater Level)

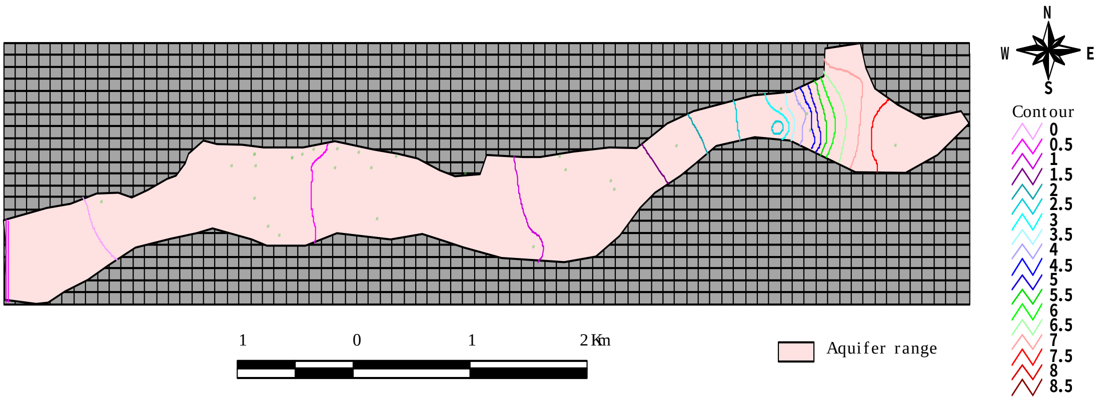


Figure 4.4.60 Results of Reproducing Calculation (Plane Distribution of Salinity)

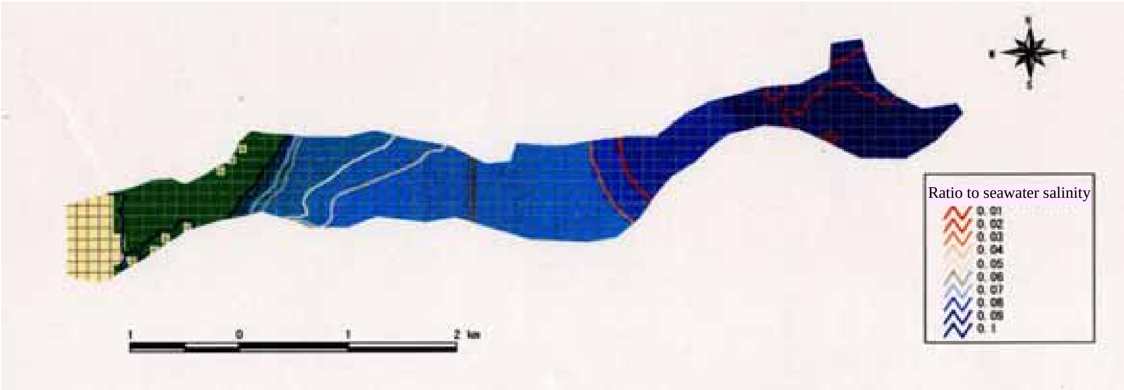


Table 4.4.14 Salinity Expression Method

	Electric Conductivity (mS/cm)	Salinity (%)	Ratio to Seawater Salinity (%)
Fresh water - Brackish water	0	0.00	0.0
	2	0.10	2.9
	5	0.28	7.8
	10	0.59	16.8
	20	1.31	37.2
	30	2.15	61.0
Seawater	44	3.52	100.0

(3) Future forecast calculation

(a) Study pattern

Regarding simulation with the 3D numerical analytical model, the dam axis of the subsurface dam was assumed to be 3.5 km from the coast to quantitatively evaluate the effect of the subsurface dam against salt water infiltration and the exploitable water quantity. The calculation period was set to 20 years and the forecast calculation was repeated using the rainfall pattern in the five years from 1997 to 2002. Therefore, the groundwater yield should be set within the range not exceeding the total quantity of water charged into the assumed subsurface dam reservoir area in the last five years.

The forecast calculation stops when the groundwater level falls and the wells run dry. Therefore, the well location and yield conditions were set so that the groundwater would remain in all wells in the 20-year calculation period. To secure as great a groundwater yield as possible, the influences of the subsurface dam construction on “groundwater level change” and “saltwater behavior” were verified by changing the pumping position and depth. The forecast calculation was repeated to verify that the groundwater level would recover. Then groundwater yield was regarded as appropriate.

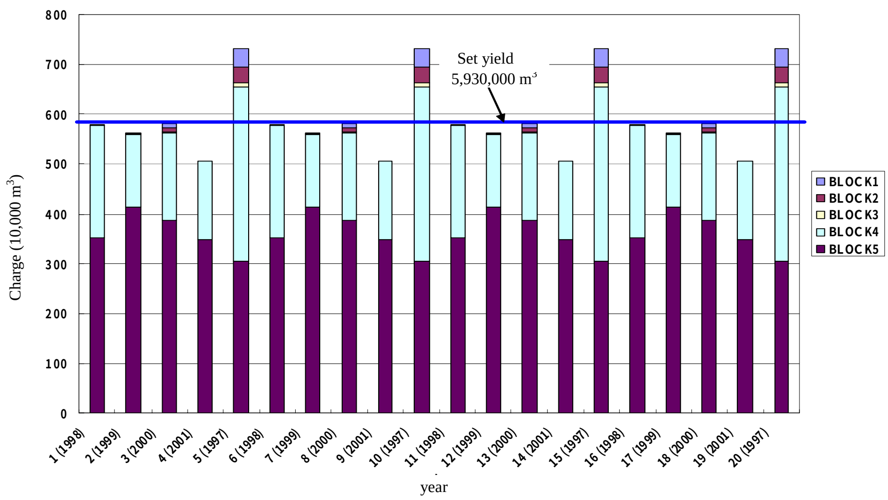
(1) All pumping wells are shifted to the upstream of the assumed subsurface dam.
(2) The wells are integrated and abandoned for intensive pumping from deep wells.

Table 4.4.15 Conditions of Forecast Calculation

Setting calculation period	July 2003 to June 2023 (20 years)
With no subsurface dam	○
With subsurface dam	○
Constant head altitude on the west coast	-0.5 m
Yield	Total yield: 5,930,000 m^3/year
Hydraulic conductivity	2×10^{-2} to 1×10^{-2} cm/s
Porosity	Block 1: 0.3 Block 2: 0.3 Block 3: 0.2
Groundwater charge	4 years from July 1998 to June 2002 + 1 year from July 1997 to June 1998 = 5 years total Monthly average (mm/day) in 20-year total by repeating this pattern four times
Initial water level	July 2003
Initial salinity concentration	July 2003
Dispersion coefficient	Vertical: 50 m, horizontal: 10 m
The Guadalupe River	Modeling using the River Leakage Package
Pond on sand-dug site	Same as above

Figure 4.4.61 Pumping Well Locations and Set Water Quantities

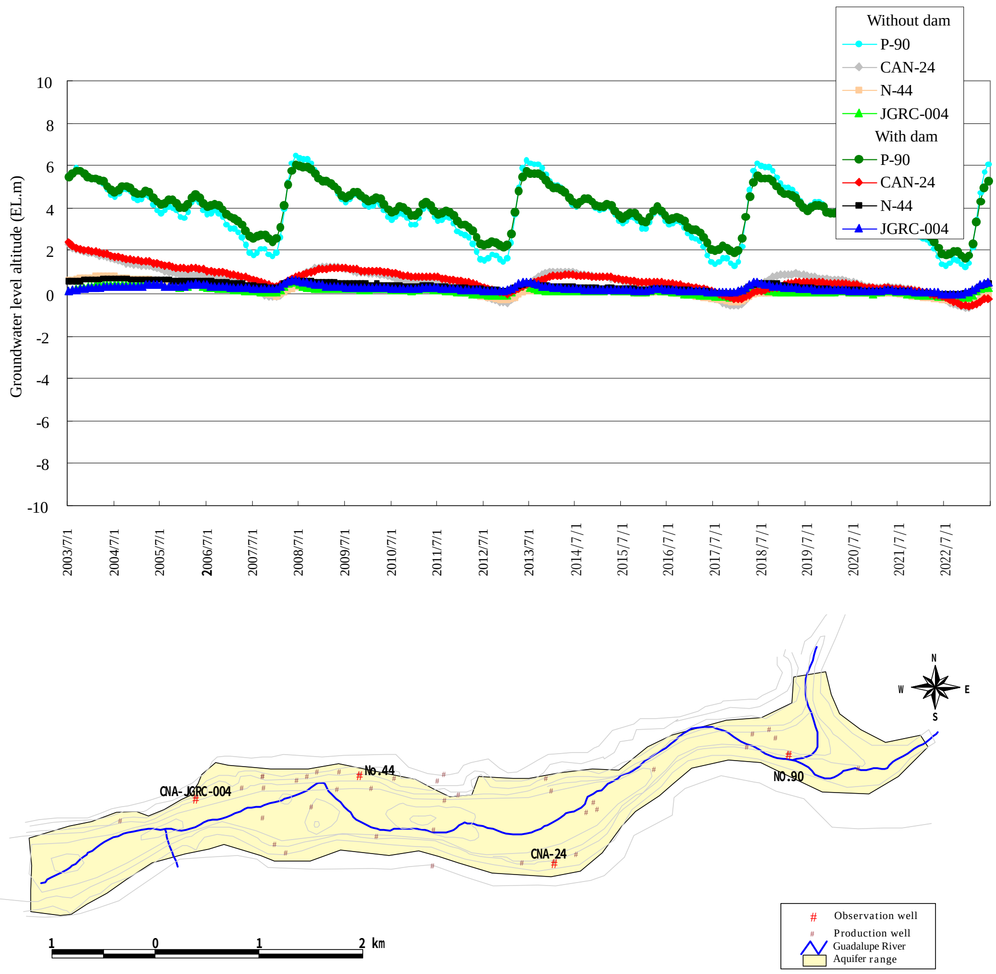
Figure 4.4.62 Changes of Charge and Set Yield Over Time



(b) Calculation results

The sustainable yield was found to be 5,930,000 m^3/year. This water quantity is about 10% down from the current total yield and must be suppressed to the level in the first half of the 1980s. Figure 4.4.63 forecasts groundwater level changes with the passage of time at this groundwater yield. There are no great differences between changes with and without the subsurface dam. Similarly, no significant differences in salinity concentration can be seen between them.

Figure 4.4.63 Forecast Groundwater Level Changes Over Time



(4) Study of subsurface dam operation plan

(a) Anti-flood measures

In La Mision, the current annual mean yield exceeds the annual mean groundwater charge. In a rainy year (large groundwater charge), however, the groundwater charge may exceed the yield, raising the groundwater level and allowing part of the groundwater to flow into the sea as dead runoff. The subsurface dam is expected to block this kind of dead runoff ground, to increase the available groundwater quantity, and to prevent surface inundation.

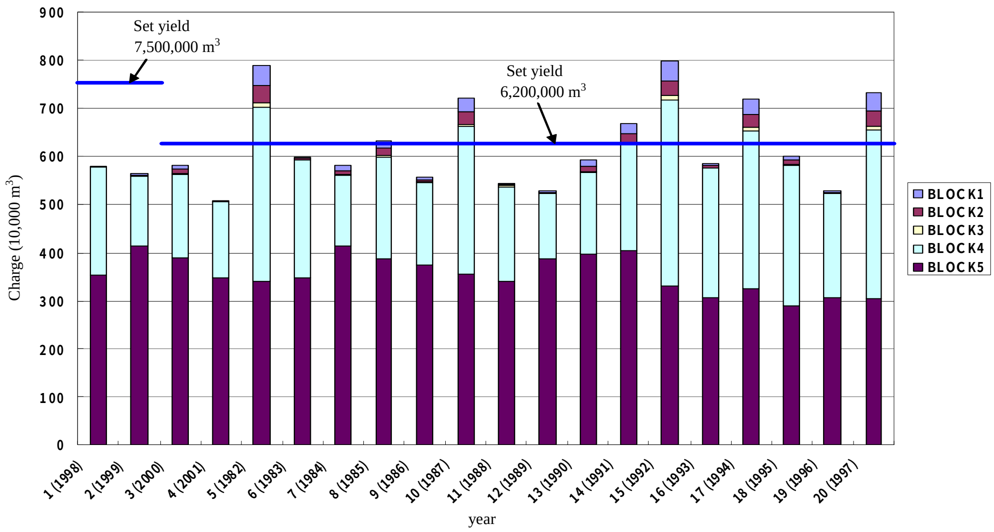
As one of the measures, the groundwater level in the assumed subsurface dam reservoir area is lowered in advance to accept as much of a flood as possible in a rainy year and recover the groundwater level. In other words, by regarding the subsurface dam reservoir area as a flood control reservoir, the groundwater level is lowered upon implementation. Using the sustainable annual yield (5,930,000 m^3) studied in (3) or slightly more, study how much the initial water level can be lowered. However, water shall not flow in at more than 2 mS/cm and the wells shall not run dry during the 20-year operation (using the rainfall pattern from 1982 to 2001).

This study will verify whether the subsurface dam has sufficient capacity for accepting a flood and will also evaluate the effects of subsurface dam construction, such as cut-off. Table 4.4.16 and Figure 4.4.64 give the conditions of calculation. The pumping wells are located as shown in Figure 4.4.61.

Table 4.4.16 Conditions of Calculation for Anti-flood Subsurface dam Operations

Set calculation period	July 2003 to June 2022 (20 years)
Constant head altitude on the west coast	-0.5m
Yield	Total yield: 6,200,000 m^3/year
Hydraulic conductivity	2×10^{-2}cm/s - 1×10^{-2}cm/s
Porosity	Block 1: 0.3 Block 2: 0.3 Block 3: 0.2
Groundwater charge	Four years from July 1998 to June 2002 + 16 years from July 1982 to June 1998 Monthly average (mm/day) in 20-year total
Initial water level	July 2003
Initial salinity concentration	July 2003
Dispersion constant	Vertical: 50 m, horizontal: 10 m
The Guadalupe River	Modeling using the River Leakage Package
Pond on sand-dug site	Same as above

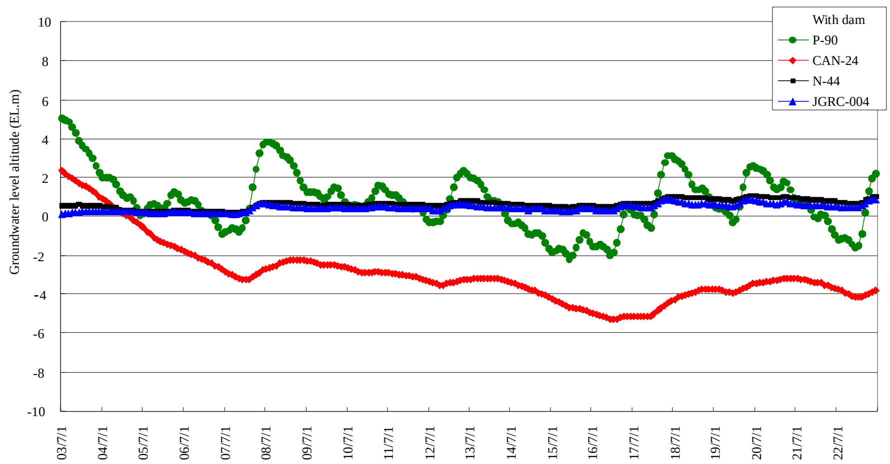
Figure 4.4.64 Changes of Charging and Set Yield Over Time



To lower the groundwater surface to a specified level within two years after subsurface dam construction, the yield was set much greater than the charge. During the two years, the groundwater level was lowered about 4 m directly upstream of the subsurface dam. When the yield was then set to 6,200,000 m^3/year, the wells never ran dry and the groundwater level fluctuation stabilized with the passage of time. This annual yield is about 300,000 m^3 more than the yield set in (3).

The difference between yield and charge was about 3 million m^3 in the first two years. This means that the reservoir can accept a flood of up to about 3 million m^3 at a time.

Figure 4.4.65 Forecast Groundwater Level Changes Over Time



(b) Installation of drainage canal

Even after implementing the above anti-flood measures by groundwater level management, heavy rainfall within a short time may cause surface inundation if the overflowing river water does not permeate into the ground. Therefore, it was proposed to forecast the range and depth of surface inundation assumed in the case of heavy rainfall and to install a canal for draining the flood.

For the heavy rainfall, the three-day rainfall (192 mm) recorded in 1980 was assumed. This was the heaviest rainfall recorded in the past 30 years. Figure 4.4.66 shows the results of forecast surface inundation. The inundation depth was forecast to be the greatest in 20 years after heavy rainfall.

Figure 4.4.66 Forecast Surface Inundation (20 days after heavy rainfall)

Water level - Ground surface (m)

Figure 4.4.67 shows the forecast surface inundation when a drain is installed. The drain will lower the water level about 0.5 m.

Water level - Ground surface (m)

Figure 4.4.67 Forecast Surface Inundation with Drain (20 days after heavy rainfall)

4.4.6 Feasibility of subsurface dam development

(1) Dam axis setting and dam dimensions

With the results of survey so far, the dimensions of the subsurface dam probable in this region (La Mision subsurface dam) were studied. The dam axis position was assumed by considering the following conditions:

- Low-permeability siltstones (basement rocks) are forming an underground valley.
- The reservoir layer is distributed broadly (thickly) at the upstream of narrow in the underground valley. This is efficient because a large quantity of water can be stored although the work sectional area of the cut-off wall is small.
- The basement top is not deeper than where a cut-off wall is feasible technically and economically (assumed depth: 60 m max).
- To inhibit saltwater infiltration and store as much water as possible, the dam axis set at the most downstream position. Whenever possible, however, the reservoir area should exclude part of the

aquifer already salinized.

To satisfy the above conditions, the dam axis was set about 3.5 km upstream from the mouth of the Guadalupe River. From the results of the past survey, Table 4.4.17 gives the outline dimensions of the subsurface dam in this region.

Table 4.4.17 Assumed Dimensions of the La Mision Subsurface Dam

Item	Description
Subsurface dam function	Cut-off wall to block salt water infiltration from the sea into the aquifer and to make an effective use of groundwater in the reservoir area
Dam axis position	About 3.5 km upstream from the mouth of the Guadalupe River
Cut-off wall	Dam crest elevation : EL.+1 m Dam length : 500 m Dam height : 60 m Overflow freeboard : 1.6 m (Lowest ground altitude on dam axis: EL.+2.6m) Cut-off sectional area : 21,000 m^2
Reservoir function	Catchment area : About 463 km^2 Reservoir area : About 2.3 km^2 gross reservoir capacity : About 8.5 million m^3 (assumed effective porosity: 0.15)
Subsurface dam facilities	Cut-off wall, drainage facilities, observation, operation, and maintenance facilities, (aquifer charging facilities)
Cut-off wall construction method	Diaphragm wall (bucket excavation method, etc.)

(2) Cut-off wall construction method

In Mexico, a diaphragm wall is used for the foundation work of a surface dam or a building or the water sealing work of a dock. To clarify the feasibility of cut-off wall construction for a subsurface dam, major civil engineering companies were surveyed by hearing and reference materials were collected about technology, machinery, and expenses in Mexico.

For diaphragm wall construction, bucket exacavator made by Soletanche (France) and bucket exacavator and horizontal multi-axial operating excavator made by BAUER (Germany) are leased or purchased.

A diaphragm wall is made of cement, bentonite, and gravels. Their combination determines the strength, permeability, and wall material price. The hydraulic conductivity of the wall may be of 10^{-6}cm/s or less.

One of the bucket exacavator, Soletanche KS3000, can excavate up to about 50 to 60 m deep. A bucket exacavator is mainly used to excavate unconsolidated sediments and, when excavating rocks, can usually deal with only soft rocks of unconfined compression strength not more than about 5 to 6 MN/m^2 (50 to 60 kgf/cm^2). This machine may cause a collapse of groove face when excavating an unconsolidated layer near the surface but can prevent the collapse with metal-made hole mouth protective casing and mud water.

If a rock of one meter or greater in the unconsolidated sediments makes excavating with a bucket difficult, a steel-made bit is dropped to crack the rock. While a bucket exacavator cannot dig more than soft rocks, a horizontal multi-axial operating excavator can dig even hard rocks. However, bucket exacavator generally costs higher than horizontal multi-axial operating excavator.

Table 4.4.18 gives an example of diaphragm wall construction in Mexico. Figures 4.4.68 to 4.4.70 show examples of construction machines.

Table 4.4.18 Example of Diaphragm Wall Construction

Location	Description of works
Veracruz	When constructing a dock in a place projecting to the coast, a diaphragm wall was constructed around the rectangular dock to cut off water. (Wall height: 23 m, wall thickness: 0.8 m) Wall materials: Water:bentonite:cement = 73:5.1:21. Hydraulic conductivity: 6.0×10^{-6}cm/sec Unconfined compression strength: 578 kN/m^2 (5.9 kg/cm^2)
Tuxpan in Veracruz	Wall height: 9.5 m, wall length: 360 m, wall thickness: 0.6 m Wall materials: Water:bentonite:cement = 73:5.3:21.7 Hydraulic conductivity: 1.3×10^{-6}cm/sec Unconfined compression strength: 647 kN/m^2 (6.6 kg/cm^2)
Aguamilpa Dam in Nayarit	Wall height: 40 m, wall length: 200 m, wall thickness: 0.8 m
El Batan Dam in Queretaro	

Figure 4.4.68 Examples of Diaphragm Wall Construction Using Bucket Exacavator

Figure 4.4.69 BAUER Bucket Exacavator (DGH)

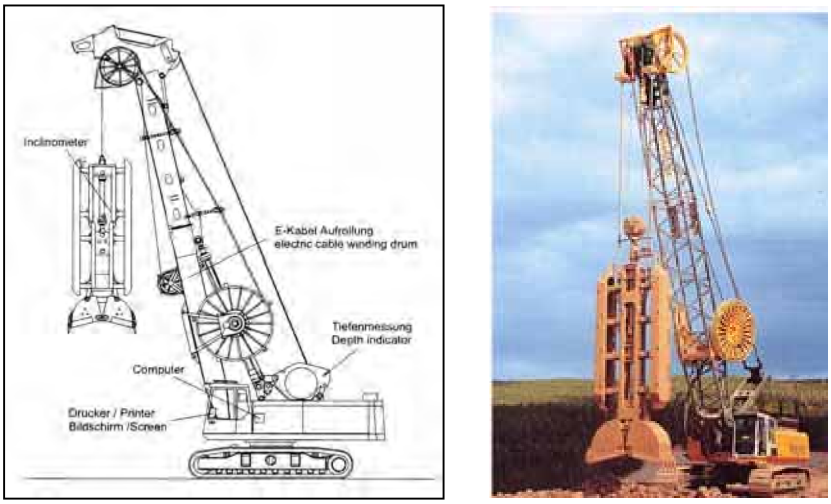


Figure 4.4.70 BAUER Horizontal Two-axial Operating Excavator (Trench Cutter)

The conditions of cut-off wall construction in this region are as follows:

- The maximum excavation depth is about GL. -60 m.
- The cut-off wall extension is about 500 m and the dam axis is assumed to be almost linear.
- Most of the construction section is a ravine plain showing comparatively flat topography. The abutments on both banks of the valley require construction work on gentle to comparatively steep slopes.
- The dam axis area is mainly composed of devastated land including riverbeds and farmland. However, the abutments partially cross roads and housing lots.
- Geologically, the object of excavation is composed of alluvium, basalt, and siltstones. In a survey so far, the alluvium was found to contain small to medium-sized gravels and not huge gravels. The siltstones range from strongly weathered cataclastic ones to comparatively fresh consolidated ones. The basement siltstones are equivalent of soft rocks.
- The alluvium is mostly dug. The basement siltstones are dug about several meters deep and a cut-off wall is penetrated.

- At the right-bank abutment, the stratum may be disturbed by landslide and other.
- If the dam width is 0.5 to 1.0 m, the design hydraulic conductivity shall be about 1×10^{-6} cm/s or less.

(3) Design of drainage facilities

Cut-off wall construction blocks the groundwater flow through the dam axis. If an adequate quantity of water is not pumped in the reservoir area, the reservoir level rises. The increased groundwater overflows between the dam crest and the surface (overflow section) to the downstream catchment area. The overflow freeboard is only less than several meters near the riverbed on the assumed dam axis of the La Mision subsurface dam and the quantity of groundwater overflowing the cut-off wall is limited. Therefore, great groundwater charge may raise the reservoir level and cause the groundwater to well up to the surface.

The range from the dam axis to 2 km upstream shows comparatively gentle topography and an excess rise of reservoir level is anticipated to pose a problem. A rise of reservoir level will be a problem in farmland of a comparatively low altitude from about 3 to 5 m.

The drainage facilities shall be a combination of drainage canals for surface water and underdrains for groundwater. The surface water drainage canals link the current riverbeds and sand-dug sites and secure adequate cross sections for draining. The underdrains are installed about 3 to 5 m under the ground to connect flow ends to the surface water drainage canals.

(4) Subsurface dam construction expenses

Major civil engineering work companies in Mexico were requested to make estimates about cut-off wall construction for the subsurface dam in La Mision. According to the estimates, the cut-off wall construction using the bucket exacavator KS3000 will cost about US 12 to 15 million dollars.

In Mexico, surface dams with reservoir capacities from about several million to 20 million m^3 cost about US 2 to 50 million dollars when constructed in 1980s to 1990s. Most of them were constructed at US 4 to 7 million dollars. Direct comparison is difficult but the La Mision subsurface dam will cost slightly higher than surface dams of about equivalent reservoir capacities.

About the running costs for tap water supply, reference data is available from the case of CESPE supplying tap water around Ensenada to Tijuana. CESPE now has four tap water sources, including one in La Mision. The maintenance and management costs for tap water supply (including pump run, equipment repairs, and labor) are US 0.05 to 0.2 dollars/m^3, depending on the water source. Water supply from La Mision costs US 0.2 dollar/m^3, highest among the four.

(5) Agricultural development potentials

(a) Land uses

The agricultural area in Baha, California is 303,660 ha (1998), about 4.3% of the total area. About 65% of the area, 198,000 ha, is irrigated farmland.

Table 4.4.19 classifies the planting areas for cyclic produce and permanent produce.

Table 4.4.19 Irrigated and Rainwater Planting Areas in 1997

Cyclic produce	Irrigated area	(ha)	172,180
	Rainwater area	(ha)	39,553
	Total	(ha)	211,733
Permanent produce	Irrigated area	(ha)	32,955
	Rainwater area	(ha)	2,762
	Total	(ha)	35,717

Source: El Sector Alimentario en Mexico Edition 1999 INEGI

To check the current land uses in La Mision, satellite images photographed by LANDSAT in 1996 and 2001 were analyzed. The spatial resolution was 30 m for the image in 1996 and 15 m for that in 2001. By using the three bands (R, B, G: 4, 3, 2), false color (Falso Color) images were created to highlight red at vegetation. Figure 4.4.71 shows the satellite image of La Mision in 1996.

In addition, the actual land uses were checked by field survey, the positions were measured using GPS, and the cultivated produce was surveyed by hearing. By integrating the results of satellite image analysis and field survey, the land uses were classified into natural grassland, natural woodland (shrub), pastureland, farmland, and waters.

In this region, sands had been collected from the riverbeds of the Guadalupe River and the lowland and flatland since 1980s. Now sand collection is prohibited under the guidance of CNA but the past sand-dug sites are left as concaves. Figure 4.4.72 shows the sand-dug sites and farmland in the ravine pine of this region.

Figure 4.4.71 Satellite Image of La Mision

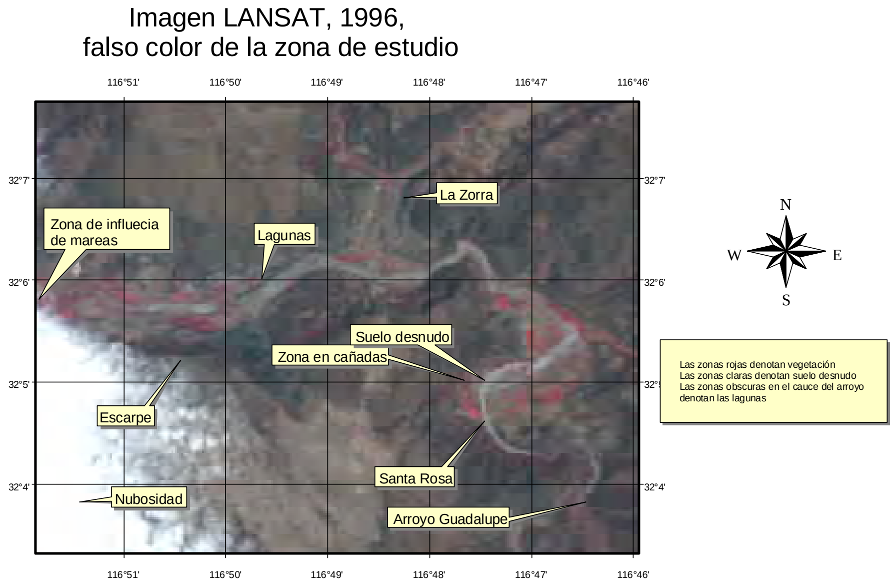
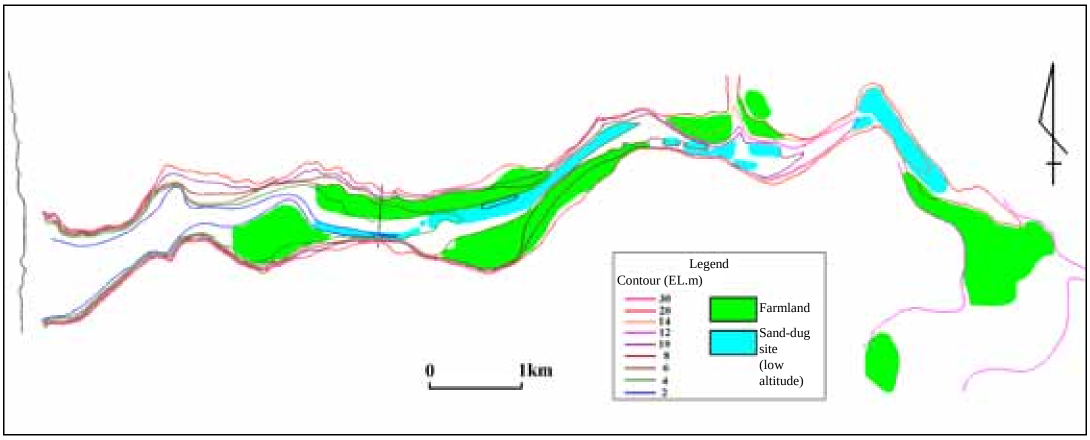


Figure 4.4.72 Sand-dug Site and Farmland Distributions



(b) Agricultural production

Baha in California, blessed with temperate climate conditions and soil conditions, allows year-round cultivation if only water is available. One farm household owns land of about 5.5 ha in average (1990). One family basically works on their own farm by employing seasonal laborers for seeding and harvesting.

Under these conditions, the irrigation rate is as comparatively high as 65%. This region just satisfies the requirements for intensive farming. Table 4.4.20 lists the yields and unit yields of main agricultural produce.

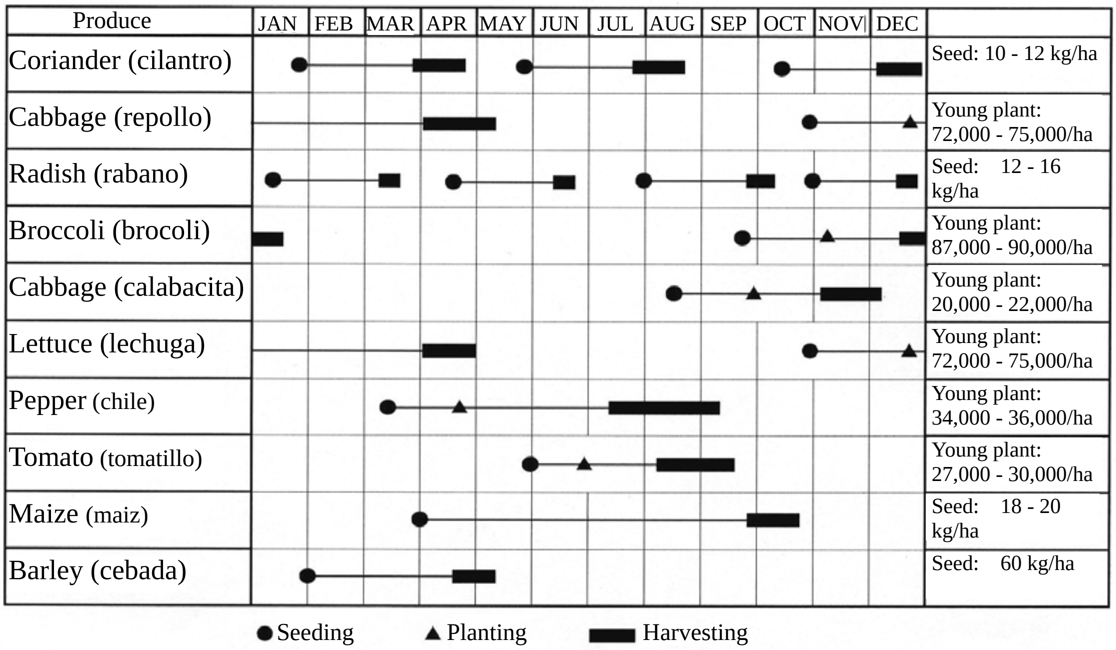
Table 4.4.20 Main Agricultural Produce in Baha, California (1997)

Produce	Harvest area (ha)	Yield (t)	Unit yield (t/ha)
Green tomato	10,233	456,262	44.6
Grape	4,708	51,566	11.0
Wheat	69,032	415,875	6.0
Strawberry	363	7,623	21.0
Safflower	2,241	4,761	2.1
Lemon	233	3,570	15.3
Green pepper	1,048	18,792	17.9
Orange	326	5,124	15.7
Barley	488	2,121	2.7
Sorghum	7,744	32,204	4.2
Potato	200	6,517	32.6
Apple	62	170	2.7
Peach	35	123	3.5
Avocado	22	89	4.0
Maize	1,821	6,704	3.7
Kidney bean	121	50	0.4

Source: El Sector Alimentario en Mexico Edition 1999 INEGI

Figure 4.4.73 show the standard planting of main vegetables and other produce in La Mision and surrounding areas.

Figure 4.4.73 Standard Planting of Main Vegetables and Other Produce



(c) Survey about farming

- Farm producing grapes for wine

There is groundwater-irrigated farmland of about 3,000 ha in the basin at the upstream of La Mision and the midstream catchment area of the Guadalupe River. Of the farmland, about 2,000 ha is used for grape cultivation (grape-cultivating population: about 1,000). Wines are also produced in this area.

This area is surrounded by mountains and suitable for grape cultivation. Olives, vegetables, and alfalfa as feed are also produced.

- La Mision

La Mision has farmland of about 4,800 ha. Of the farmland, about 200 ha is groundwater-irrigated farmland, 1,280 ha is rainwater farmland, and 3,320 ha is pastureland in summer. The farmland us is restricted by topographical conditions. At the bottom of a valley along the Guadalupe River is irrigated farmland of about 10 m in altitude. This farmland is a two-crop area mainly producing vegetables, such as blue pepper, tomato, coriander, cabbage, radish, broccoli, pumpkin, and lettuce. The rainwater farmland on a plateau of about 20 m in altitude is producing mainly livestock feed, such as barley and oat. Plateaus, slopes unsuitable for farming, and devastated land are used as pastureland in summer.

One farm household owns land of 40 to 50 ha in average. About 3 to 4 ha of the land is irrigated farmland. In this area, more than half the farm households are also breeding livestock. The cattle population is said to be over 1,000. Irrigation is mostly of the trickle type.

Table 4.4.21 Cultivation of Main Vegetables and Produce in La Mision

	Quantity	Seeding Harvesting	Fertilizing Irrigation	Average yield
Green pepper CHILE	Seed: 2.5 kg/ha Young plant: 34000 - 36000	2/15 - 4/15 120 days after seeding (Uniform germination and growth	N: 200 kg/ha Between ridges by trickle P: 60kg/ha K: 60kg/ha	12.2 t/ha (20 t/ha)
Coriander CILANTRO	10 - 12 kg/ha	Year-round 50 to 60 days after seeding (Uniform germination and growth	N: 150 kg/ha Between ridges P: 30kg/ha	8 t/ha (20 t/ha)
Green tomato TOMATILLO	Seed: 2.0 kg/ha Young plant: 27000-30000	4/1 - 6/30 60 to 80 days after seeding	N: 150 kg/ha Between ridges by trickle P: 50kg/ha	10 t/ha (20 t/ha)
Radish RABANO	12 - 16 kg/ha	Year-round 40 days after seeding (Uniform germination and growth)	N: 150 kg/ha Between ridges P: 60kg/ha	10 t/ha (35 t/ha)
Broccoli BROCOLI	Seed: 2 - 2.5 kg/ha Young plant: 87000-90000	9/1 - 11/15 80 to 100 days after seeding	N: 180 kg/ha Between ridges by trickle P: 60kg/ha K: 60kg/ha	12 t/ha (18 t/ha)
Pumpkin CALABACITA	Seed: 4.5 kg/ha Young plant: 20000-22000	7/16 - 9/30 60 to 80 days after seeding	N: 160 kg/ha Between ridges by trickle P: 60kg/ha	11 t/ha (25 t/ha)
Lettuce LECHUGA	Seed: 1.5-2 kg/ha Young plant: 72000-75000	9/1 - 12/31 150 days after seeding	N: 160 kg/ha Between ridges by trickle P: 60kg/ha	19 t/ha (25 t/ha)
Cabbage REPOLLO	Seed: 2.5 kg/ha Young plant: 72000-75000	9/1 - 12/31 150 days after seeding (Uniform germination and growth)	N: 150 kg/ha Between ridges P: 60kg/ha	20 t/ha (31 t/ha)
Maize MAIZ(grano)	18 - 20 kg/ha (50,000-55,000/ha)	3/1 - 4/30 180 days after seeding	N: 120-150 kg/ha Between ridges P: 50-60kg/ha	3.5-8.0 t/ha (7.0-14t/ha)
Barley CEBADA	Two-season seeding: 60kg/ha	11/1 - 4/1 1/15 - 6/15	N: 160 kg/ha Between ridges12cm P: 60kg/ha	4 - 8 t/ha (6-18 t/ha)
Oat AVENA (Rainwater)	Scattering: 100 kg/ha Grooving: 80kg/ha	11/1 - 1/31 Pasture after bearing	N: 50 kg/ha (Good year) P: 30kg/ha(Ditto)	

* ( ): Possible yield

Tables 4.4.22 and 4.4.23 give agricultural production data.

Table 4.4.22 Agricultural Production (1998 to 1999: Planting in fall and winter, with irrigation)

	Area (ha)		Yield	Yield	Labor force
	Seed	Harvest	(t/ha)	(dollar)	
Barley (cebada)	14	14	3.00	58,000	16
Coriander (cilantro)	12	12	7.36	288,300	26
Cabbage (repollo)	10	10	29.89	336,800	63
Radish (rabano)	9	9	9.03	138,400	65
Broccoli (brocoli)	5	5	19.40	96,400	53
Cabbage (calabacita)	4	4	14.00	95,000	65
Lettuce (lechuga)	1	1	12.62	40,000	66
Total	55	55		1,052,900	354

Table 4.4.23 Agricultural Production (1998 to 1999: Planting in fall and winter, with rainwater)

	Area (ha)		Yield (t/ha)	Yield (dollar)	Labor force
	Seed	Harvest			
Oat (avena)	95	95	2.9	76,000	143
Barley (cebada)	32	32	2.0	37,296	48
Total	127	127		113,296	191

4.5 Summary

Based on the results of surveys conducted in Indonesia and Mexico, this section discusses the survey accuracy, expected effects of the project, and future subjects.

4.5.1 Ketes in Indonesia

The new exploitable water quantity by subsurface dam could be roughly calculated. The maximum area farmed with this water was also calculated. These numeric values were obtained by comparing the measured and calculated groundwater levels in hydraulic analysis. The hydraulic conductivity, effective porosity, and other parameters used for hydraulic analysis do not conflict with the empirical values in terms of geological facies and rock facies. Therefore, there may not be any significant problems concerning the reliability of hydraulic analysis results.

The most prospective method of constructing a cut-off wall for a subsurface dam is grouting. However, it is not known whether a wall satisfying the design hydraulic conductivity of 10^{-5} cm/sec can be constructed. This should be checked by trial construction, which would also be needed to estimate the construction requirements and approximate project expenses.

The estimated project expenses are supposed to include channel construction costs. If the maximum benefiting area is considered, however, it is difficult to assume water supply out of the catchment area. Therefore, most of the project expenses may be spent on the construction of a cut-off wall.

In this region, deep groundwater development and surface water development with a diversion weir are also anticipated. Therefore, it is preferable to select a water resources development method by checking against the water utilization plan under study mainly by local residents.

4.5.2 La Mision, Mexico

Judging from the tendency of the groundwater level falling with the passage of time, groundwater pumping in this region is obviously excessive. This problem cannot be solved by subsurface dam construction but instead requires a certain restriction on groundwater intake. The effect of subsurface dam construction in this region depends on how much the restriction on groundwater intake can be reduced.

Since a subsurface dam of saltwater infiltration prevention is studied in this region, a secure cut-off characteristic is expected. The cut-off wall construction method now assumed is to excavate a groove and replace the walls completely with artificial ones. The replaced sections will have a secure cut-off characteristic. However, note that this construction will not be easy because the construction depth is as extensive as about 60 m and the geology to be dug is composed of unconsolidated gravels whose groove walls collapse easily. In addition, the following geological area requires appropriate foundation treatment because the possibility of roundabout percolation cannot be denied. In some cases, a design change in cut-off and depth may become necessary, increasing the project expenses.

* Right bank of the dam axis

Because of the complicated geologic structure, the cut-off range has not yet been determined.

* Fracture zone

If not very weathered or cracked, siltstones to be used as the hydraulic basement have low permeability and do not require special treatment. However, siltstones that are crushed, cracked, or weathered near faults or their surroundings show high permeability and are not appropriate as the basement of the subsurface dam. In this region, faults are estimated to be distributed parallel with the valley.

In this region, the groundwater charge fluctuates greatly between years. More groundwater than charged is pumped in a dry year but dead runoff may be substantial in a rainy year. The purpose of constructing a subsurface dam is to solve the discrepancy between groundwater charge and intake. Therefore, handling surface water in a rainy year is important. The permeation of surface water into the ground should be promoted by lowering the groundwater level in advance and charging groundwater artificially.

The influence of subsurface dam construction on the ambient environment differs greatly between the downstream and upstream sides of the cut-off wall. On the downstream side, the groundwater flow rate decreases, promoting salinization and possibly inducing salt damage to soil. Therefore, the downstream area should be compensated for subsurface dam construction. On the upstream side, the groundwater level may rise. Where inundation is anticipated, drainage canals and underdrains should be installed to drain overflow water.

Even when the groundwater yield from the entire region is the same, merely moving the intake position inland will ease groundwater salinization. Before studying the feasibility of subsurface dam construction, it is important to achieve a full consensus of residents and groundwater users regarding the groundwater intake method.

Chapter 5 Design

5.1 Basic Policy of Design

5.1.1 Basics about design

A subsurface dam consists of a cut-off wall, intake facilities, drainage facilities, operation and maintenance facilities, and groundwater aquifer charging facilities. These facilities should be designed to have the necessary functions of a subsurface dam and to be environmentally friendly by considering the ambient natural and social conditions. In addition, it is important to minimize the construction costs and future maintenance and management costs of the subsurface dam.

A subsurface dam can be designed efficiently by referencing past designs and construction works. Table 5.1.1 introduces main subsurface dam construction in the past. Table 5.1.2 introduces installations of intake, drainage, and aquifer charging facilities.

Table 5.1.1 Subsurface dam Construction

Dam Name	Location	Use	Dam Type	Top Length (m)	Height (m)	Width (m)	Cut-off Area (m)	Bottom Altitude (m)	Total Reservoir (m^3)	Year of Completion	Main Method	Depth of Construction (m)	Aquifer	Basement Geology
Kabashima	Nagasaki Pref., Japan	Water supply	Saltwater infiltration prevention	74	27	3.0	1,000	-22	20,000	1974	Stage grouting Twin-pipe grouting	27	Alluvial gravel layer	Metamorphic rock
Tsunegami	Fukui Pref., Japan	Water supply	Saltwater infiltration prevention	204	18.5	0.5	3,300	-22	73,000	1983	Bucket excavation	22	Alluvial gravel layer	Metamorphic rock
Miko	Fukui Pref., Japan	Water supply	Saltwater infiltration prevention	196	39	0.5	5,033	-37	23,000	1996	Cast-in-place deep mixing	42	Alluvial gravel layer	Weathered rock
Nakajima	Ehime Pref., Japan	Irrigation	Saltwater infiltration prevention	88	24.8	0.5	1,284	-23	22,200	1992	Cast-in-place deep mixing	28	Alluvial gravel layer	Tertiary volcanic rock
Komesu	Okinawa Pref., Japan	Irrigation	Saltwater infiltration prevention	2,432	69	0.5	124,800	-65	3,457,000	2003	Cast-in-place deep mixing Stage grouting	86	Limestone	Tertiary mudstone
Senbaru	Okinawa Pref., Japan	Irrigation	Saltwater infiltration prevention	550	13	0.55	5,400	-12	240,000	Under construction	Steel sheet pile	13	Alluvial gravel layer	Cretaceous mudstone
Tengakuma	Fukuoka Pref., Japan	Water supply	Afflux	129	12.5	3.0	950	153	17,500	1988	Twin-pipe grouting (partially stage grouting)	20	Alluvial gravel layer	Granite
Waita	Nagasaki Pref., Japan	Water supply	Afflux	105	7.5	0.5	750	-7	12,000	1992	Bucket excavation	10	Alluvial gravel layer	Cretaceous volcanic rock
Minafuku	Okinawa Pref., Japan	Irrigation	Afflux	500	16.5	5.0	4,800	14	700,000	1979	Stage grouting	34	Limestone	Tertiary mudstone
Sunagawa	Okinawa Pref., Japan	Irrigation	Afflux	1,677	50	0.5	43,147	-19	9,500,000	1993	Cast-in-place deep mixing Stage grouting	65	Limestone	Tertiary mudstone
Fukusato	Okinawa Pref., Japan	Irrigation	Afflux	2,908	27	0.5	42,168	19	10,500,000	1998	Cast-in-place deep mixing Stage grouting	56	Limestone	Tertiary mudstone
Kikai	Kagoshima Pref., Japan	Irrigation	Afflux	2,280	34	0.5	45,100	-14	1,800,000	1999	Cast-in-place deep mixing	44	Limestone	Tertiary mudstone
Giiza	Okinawa Pref., Japan	Irrigation	Afflux	969	53	0.5	31,400	-25	390,000	2001	Cast-in-place deep mixing	56	Limestone	Tertiary mudstone
Yokatsu	Okinawa Pref., Japan	Irrigation	Afflux	705	67.6	0.5	22,500	-42	3,963,000	Under construction	Cast-in-place deep mixing		Limestone	Tertiary mudstone
Kanjin	Okinawa Pref., Japan	Irrigation	Afflux With surface reservoir	1,088	52	0.5	30,000	-26	1,580,000	Under construction	Cast-in-place deep mixing	57	Limestone	Tertiary volcanic rock
Sekkan	Bouko Archipelago, Taiwan Bouko Archipelago, Taiwan	Water supply	Saltwater infiltration prevention	820	24	0.55	28,300	-15	1,277,000	1986	Vertical multi-axis excavation	25	Lime sandstone	Volcanic rock
Long kou	Shandong Province, China		Afflux With surface reservoir	6,000	40		160,000		53,590,000	1994	Jet grout			
Long he	Liaoning Province, China		Afflux With surface reservoir	6520	12	0.4			640,000	Under construction	Jet grout		Quaternary gravel layer	
San jian bu	Liaoning Province, China	Irrigation	Afflux With surface reservoir	1,200	23	0.4		-23	6,142,000	Planned	Jet grout		Quaternary gravel layer	Jurassic volcanic stone
Nare	Namentenga, Burkina Faso	Irrigation	Afflux	210	8	3 – 8			800,000	1999	Open-cut (cohesive soil consolidation)	11	Tertiary sedimentary stone	Granite
Diplo	Pangasinan, the Philippines	Irrigation	Afflux	188	18	0.8		162		1995	Open-cut (ferroconcrete)		Alluvial gravel layer	Volcanic rock
Principal	Pangasinan, the Philippines	Irrigation	Afflux	207	12	0.8		105		1995	Open-cut (ferroconcrete)		Alluvial gravel layer	Volcanic rock

Table 5.1.2 Installations of Intake, Drainage, and Groundwater Aquifer Charging Facilities

Dam	Intake Facilities	Drainage Facilities (Other than dam overflow section)	Charging Facilities	Remarks
Kabashima	Tubular well: 4 (200 mm dia. × 20 m deep: 2, 200 mm dia × 8.5 m deep: 1, etc.)		Sand pile: 69 Charging pond: (5 × 50 m, 1 m deep) Underdrain (subsurface trench: 20-m long drain)	Constructed using the stage grout method for construction and twin-pipe grouting method for cut-off improvement.
Tsunegami	Tubular well: 5 (300 mm dia. × 30 m deep)	Underdrain (200 mm dia. × 20 m deep)	Injection well: 8 (300 mm dia. × 14 m deep in average) Permeation pond: 2 (1420 m^2 in total)	
Kamiko				
Nakajima	Tubular well: 2 (150 mm dia. × 21–27 m deep)	Underdrain: 35 (300 mm dia. × 142 m long, 200 mm dia. × 120 m long)		Experimental subsurface dam
Komesu	Tubular well: 18 (300 mm dia. × 30–47 m deep)	Underdrain Drainage tunnel, etc.		Desalinizing well is planned. Saltwater partially eliminated from the reservoir area at dam construction.
Senbaru	Underdrain (intake trench: 500 mm effective dia. × 3000 m long)	Underdrain (100 mm dia. × 1.5 m deep, 15,300 m long)		Used with surface reservoir
Tengakuma	Tubular well: 4 (200 mm dia. × 20 m deep)			
Waita	Well		Underdrain	
Minafuku	Vertical hole: 1 (3500 m dia. × 25 m deep, for intake and drainage) Horizontal hole: 2 (200 mm dia. × 100 m long, 400 mm dia × 25 m long)	Floodway horizontal hole: 2 (200 mm dia. × 100 m long, 400 mm dia. × 25 m long)		Experimental subsurface dam (for irrigation)
Sunagawa	Tubular well: 66 (400 mm dia. × 40–60 m deep)			
Fukusato	Tubular well: 81 (400 mm dia. × 40–70 m deep)			Limestone cavity processing
Kikai	Collecting well: 8 Vertical hole (3500 mm dia. × 29–36 m deep) Horizontal hole (100 mm dia. × 50 m long): 20 to 24/well	Underdrain (100–600 mm dia. × 1.5 m deep, 9557 m long) Floodway horizontal hole (350 mm dia. × 680 m long)	Permeation pond (direct permeation from indirect area into direct area)	Dam partially constructed from inside a tunnel. Four kinds of dam construction methods tested.
Giiza	Tubular well: 13 (300 mm dia. × 45–75 m deep)			
Yokatsu	Tubular well: 6 (400 mm dia. × 83 m deep)			
Kanjin	Surface water intake Vertical hole (3000 mm dia. × 24 m long) Conducting tube (horizontal hole: 800 mm dia. × 35 m long)	Spillway (surface water drainage) Floodway (417 m long), one permeation pond		Surface ponding type Limestone cavity processing
Sekkan	Tubular well: 7 (400 mm dia. × 20 m deep)			
Long kou			Permeation pond and injection well	River water stored by surface afflux facilities (auto flap gate)
Long he				River water stored by rubber dam
San jian bu	Underdrain: 4 (400 m long × 1 m dia., burial depth 4.5–6 m) Large-diameter well (on both ends of collecting underdrain)		Permeation pond: 300 (50–100 m long, 2 m deep) Injection well: 2,000 (1 m dia. × 2–3.5 m deep) Surface water reservoir facilities: 3 (upstream of subsurface dam)	Ground gate planned to prevent saltwater inflow and to store surface water. Desalinizing well planned.
Nare	Well: 3		Surface water reservoir facilities: 1 (upstream of subsurface dam)	
Diplo	Underdrain: 35 (600 mm dia. × 20 m deep, natural flow)			Substitute facilities for intake facilities buried by a disaster. Doubled as groundsill to stabilize the riverbed.
Principal	Underdrain: 35 (800 mm dia. × 24 m deep, natural flow)			Substitute facilities for intake facilities buried by a disaster. Doubled as groundsill to stabilize the riverbed.

5.1.2 Design notes

(1) Reservoir scale and facility functions

If the dam height is increased and the full reservoir level is set high, the gross reservoir capacity of a subsurface dam will increase. However, this may raise the reservoir level excessively and disturb the use of land in the reservoir area. Consequently, drainage facilities may become necessary. If the dam height is reduced and the reservoir level is set high, the adverse effects of an excessively high reservoir level will become small but the gross reservoir capacity will decrease. As the reservoir level is higher, water intake is generally easier. Reducing the dam height and lowering the reservoir level will increase the operating costs for intake.

Thus, the subsurface dam reservoir scale (reservoir level, gross reservoir capacity, reservoir area range, etc.) and the drainage and intake functions are closely related to each other. Therefore, when determining the reservoir scale and designing a cut-off wall, drainage facilities, and intake facilities, it is important to coordinate the facility functions and ensure that the design is functionally and economically optimum.

(2) Hydraulic analyses

A subsurface dam comprises facilities to control groundwater flow than cannot be seen directly. By using a computer, a groundwater simulation model is created on the basis of various survey results for hydraulic analysis. Hydraulic analysis reproduces the current groundwater flow and clarifies the groundwater flow after subsurface dam construction qualitatively and quantitatively to provide data for facility design. Table 5.1.3 lists the types and purposes of hydraulic analyses necessary for designing a subsurface dam.

Table 5.1.3 Hydraulic Analyses used for Subsurface dam Design

Analysis	Purpose
Water balance analysis	Clarify the water balance in the subsurface dam catchment area and determine the exploitable groundwater quantity and the reservoir capacity.
Intake analysis	Forecast the lowering of the reservoir level accompanying intake and the maximum quantity of intake and determine the optimum number of intake facilities and their locations and structures.
Flood analysis	Forecast the rise of the reservoir level after cut-off wall construction and determine the scales, locations, and structures of drainage facilities.
Saltwater infiltration analysis	Forecast saltwater infiltration into the aquifer and determine the dimensions of the cut-off wall and other.

(3) Uncertainty of design values

The reservoir layer of a subsurface dam is distributed underground and its components and hydraulic properties (hydraulic conductivity, effective porosity, etc.) vary between places. Therefore, it is generally difficult to grasp the distribution and hydraulic properties of a reservoir layer even by a detailed survey. At the design stage of a subsurface dam, the groundwater behaviors after subsurface dam construction are estimated by groundwater simulation and the facility dimensions and other are determined. Some parameters used for this simulation are based on presumptions or assumptions and may produce analytical errors. Therefore, some uncertainty cannot be avoided about the subsurface dam reservoir capacity, exploitable groundwater quantity, and other design values or the effects of various facilities. To evaluate whether or not the subsurface dam is exhibiting its intended functions, monitor the groundwater level and other factors during survey and planning, construction, and operation. Based on the results, facilities are added and the subsurface dam operation plan is reviewed as required.

(4) Evaluation of environmental influences and measures

A subsurface dam has a small impact on the environment, compared with a surface dam. Once a cut-off wall is constructed for a subsurface dam, however, it is almost impossible to remove the cut-off wall and restore the original status. This means that a cut-off wall may produce long-term and semi-permanent influences on the environment. When determining the location and dimensions of a cut-off wall, however, environmental influences should be fully studied and considered.

The environmental influences of subsurface dam construction can be classified into ones on the downstream of the cut-off wall and ones on the upstream.

At the downstream of the cut-off wall, the groundwater flow rate may fluctuate or decrease depending on cut-off wall construction and subsurface dam operation (intake). In a coastal area, the progress of salinization downstream of the cut-off wall may be facilitated and affect the current groundwater use. When constructing a subsurface dam, therefore, it is necessary to consider and compensate for groundwater use in the downstream area. If there is a spring (including a seabed spring) in the downstream area, cut-off wall construction may reduce the amount of spring water and affect spring water use and the ecosystem surrounding the spring.

At the upstream of the cut-off wall, cut-off raises the groundwater level. If heavy rainfall raises the reservoir level excessively, inundation or soil wetting in a low-altitude area may affect the land use and the ecosystem. In addition, blocking surface water permeation into the ground may increase the surface water flow rate. The groundwater level rise may cause salt accumulation on the soil of a dry area.

To solve these problems, forecast possible places and scales of damage by groundwater simulation or other method and reflect the results in the design, construction, and operation of the subsurface dam. When groundwater pumped from the subsurface dam is used to irrigate the catchment area, the irrigation water may partially permeate again into the subsurface dam reservoir layer and be recycled. Some researchers say that salts and other dissolved substances may be condensed in the reservoir water. Where the groundwater has a high degree of salinity from the beginning, salt accumulation and reservoir water changes by irrigation should be studied. Whether or not there is a subsurface dam, excess fertilization and other acts on farmland in the aquifer distribution area may contaminate the groundwater.

(5) Maintenance and management

A cut-off wall made of durable materials is not difficult to maintain or manage but appropriate maintenance and management are essential for intake facilities. Pumps and other equipment should also be updated at appropriate timings.

In addition, intake facilities usually require high operating costs for using a subsurface dam reservoir because power is generally used to pump the reservoir water. At the design stage, therefore, it is necessary to consider not only the construction costs for the subsurface dam but also the operating, maintenance, and management costs for the intake facilities.

Unlike a surface dam, a subsurface dam loses groundwater around the intake facilities as the groundwater is pumped. For the efficient intake of groundwater, therefore, it is important to arrange the intake facilities and apportion the intake quantity appropriately so that the groundwater level in the reservoir area remains as even as possible at intake.

5.1.3 Design notes for subsurface dams of saltwater infiltration

A subsurface dam of no saltwater infiltration has different geographical conditions and function requirements from an afflux subsurface dam. When designing a subsurface dam of saltwater infiltration prevention, note the following points:

(1) Imperviousness of cut-off wall

A subsurface dam of saltwater infiltration prevention requires higher imperviousness and construction accuracy for a cut-off wall than an afflux subsurface dam does, because inadequate imperviousness may cause saltwater infiltration into the reservoir area and salinize the reservoir water. Since the wall quality may deteriorate under the influence of saltwater, the types and mixture of cut-off wall materials must be selected carefully.

(2) Saltwater infiltration from cut-off wall and basement

A wall constructed by deep mixing or grouting is not completely impermeable but has slight permeability. Even a basement of low permeability may have permeable weathered sections or faults distributed. Because of these factors, some saltwater infiltration into the reservoir area may be inevitable if intake makes the reservoir level lower than the sea water level. To prevent this problem, determine the permeability and thickness of the wall, the depth of the penetration part, and other cut-off wall dimensions and also the dam operation plan on the basis of saltwater infiltration analysis so that the degree of saltwater infiltration will keep salinity in the reservoir area within the tolerance of water use. At the design stage, note that saltwater infiltration from a basement of inadequate imperviousness may not be solved by extending the basement penetration part of the cut-off wall to some extent.

(3) Residual saltwater in reservoir area

In a coastal area, saltwater masses are often distributed in an aquifer similar to wedges. The mixing of saltwater can be avoided by setting the dam axis at the upstream of the saltwater mass distribution area. For subsurface dam storage, however, the dam axis should be set at the most downstream position. This may allow saltwater masses (residual saltwater) to enter the reservoir area. This residual saltwater may be more than saltwater permeated from the cut-off wall and basement after cut-off wall construction. Since the saltwater is easily pumped at intake from the reservoir area, preventive measures should be well discussed, including the installation of desalinizing facilities.

(4) Anti-inundation measures for reservoir area

If the dam is high and there is not a great difference between the surface and the reservoir level, groundwater dammed by the cut-off wall may cause overflow to the surface in the case of heavy rainfall and cause inundation or wetting. A subsurface dam of saltwater infiltration prevention is often planned on low coastland when the reservoir area is topographically low and flat and the groundwater level is high. Since the dam crest elevation of the cut-off wall cannot be set lower than the sea water level, it may be impossible to reserve an adequate cut-off wall overflow freeboard and the dam crest overflow may not be enough to drain surplus water. This kind of subsurface dam requires drainage facilities in the reservoir area. However, design the drainage facilities with great care because low and flat topography may now allow a necessary gradient for a drainage canal or underdrain.

(5) Mud layer between reservoir layers

A subsurface dam of saltwater infiltration prevention is often planned in a coastal plain with the alluvium deposited in a drowned valley as the aquifer. If a soft mud layer is sandwiched between the alluvium, not only storage but also intake will be disturbed. Consolidation of the soft clay layer accompanying intake may cause land subsidence. In addition, groundwater in layers lower than a mud layer are often more saline and cannot be used. Therefore, it is necessary to determine the cut-off wall position, intake facility arrangement, and intake depth after fully grasping the mud layer position and salinization.

Where mud and gravel layers are alternated, the stratum properties greatly differ depending on the depth. Therefore, take great care regarding quality control of the cut-off wall when using the grouting method or the deep mixing method that partially captures excavated sand and gravels in the wall.

5.2 Cut-off Wall

5.2.1 Functions and dimensions of cut-off wall

A subsurface dam has two functions. One is to dam groundwater for afflux and reservoir. The other is to block saltwater infiltration. A surface-inundation subsurface dam has functions not only to dam groundwater but also to store surface water on the ground surface in the reservoir area. According to the purposes and functions of these subsurface dams, a cut-off wall is designed to secure necessary imperviousness meeting the hydrological and geological conditions of the dam site.

Reservoir water leakage and saltwater infiltration into the reservoir area that disturbs the efficient use of reservoir water occurs in the cut-off wall, at the junction between the cut-off wall and basement, and through the basement. When designing a cut-off wall for a subsurface dam, determine the design hydraulic conductivity and thickness of the cut-off wall and the length of the penetration part by assuming reservoir leakage and saltwater infiltration to limit them within the tolerances in the project. Together with measures of drainage, determine the dam height by considering the influences of reservoir level rise after cut-off wall construction on the land use. In addition, determine the design strength of the wall from the ground on the construction site.

It is economical to make the dam axis the shortest linear cut-off. However, the cut-off wall may be bent only if it is continuous.

5.2.2 Imperviousness of cut-off wall

For an afflux subsurface dam, the imperviousness of a cut-off wall is determined so that reservoir leakage from the cut-off wall will not affect water use. If necessary, intake can be secured despite some leakage from the cut-off wall by considering the balance between the groundwater inflow (groundwater charge) into the reservoir area and leakage from the cut-off wall, and the design hydraulic conductivity of the wall may be increased or the wall thickness may be reduced.

For a subsurface dam of saltwater infiltration prevention, if saltwater permeates through the cut-off wall into the reservoir area, the adverse influences of salinization on the water quality often continue for a long time. Therefore, the hydraulic conductivity and other dimensions of a cut-off wall should be determined after thorough study.

At the construction of a cut-off wall, machine hole bending and other factors generally lower the accuracy as the depth increases. This often produces a gap from the cut-off wall and makes it impossible to secure the necessary wall thickness, consequently lowering the imperviousness. When determining the dam axis position or designing the cut-off wall, consider the efficiency and accuracy of construction.

The imperviousness of a cut-off wall is determined from the hydraulic conductivity of wall materials and the wall thickness. A wall of low permeability may have adequate imperviousness even when it is thin. To the contrary, a wall of certain permeability should be thick to ensure necessary imperviousness. The wall materials and thickness are approximately determined by the cut-off wall construction method. Table 5.2.1 introduces cut-off wall construction methods and dimensions that were used in past subsurface dam construction.

Table 5.2.1 Cut-off Wall Construction Methods and Dimensions

Type	Method	Cut-off Wall Materials	Case	Wall Thickness (m)	Hydraulic Conductivity (cm/s)
Ground improvement	Twin-pipe grouting	Cement Bentonite	Kabashima	3	5×10^{-5} – 6×10^{-5} (10^{-4} units partially)
			Tengakuma	3	1×10^{-5} or less
	Stage grouting	Cement Bentonite	Sunagawa Fukusato	5	5×10^{-5} or less
Diaphragm wall	Bucket excavation	Cement Bentonite Accelerator	Tsunegami Waita	0.5	
	Cast-in-place deep mixing	Cement Adjustment slag Fly ash Bentonite Expanding and thickening agents	Sunagawa Fukusato Nakajima Komesu Giiza, etc.	0.5	1×10^{-6} or less
	Large-diameter drilling	Concrete Mortar	Komesu	0.8	7×10^{-8}
	Horizontal multi-axial operating excavation	Concrete	Komesu	0.8	2×10^{-7}

The design hydraulic conductivity and wall thickness for cut-off wall construction by grouting were determined by the following study at the Minafuku dam.

The mean hydraulic conductivity k of a catchment area including a cut-off wall of wall thickness L_2 and hydraulic conductivity k_2 can be calculated as follows:

$$k = L_1/((L_1 – L_2)/k_1 + L_2/k_2)$$

k_1: Mountain hydraulic conductivity on both sides of the cut-off wall, k_2: Hydraulic conductivity of the cut-off wall

L_1: Center distance of catchment areas on both sides of the cut-off wall, L_2: Wall thickness (dam width)

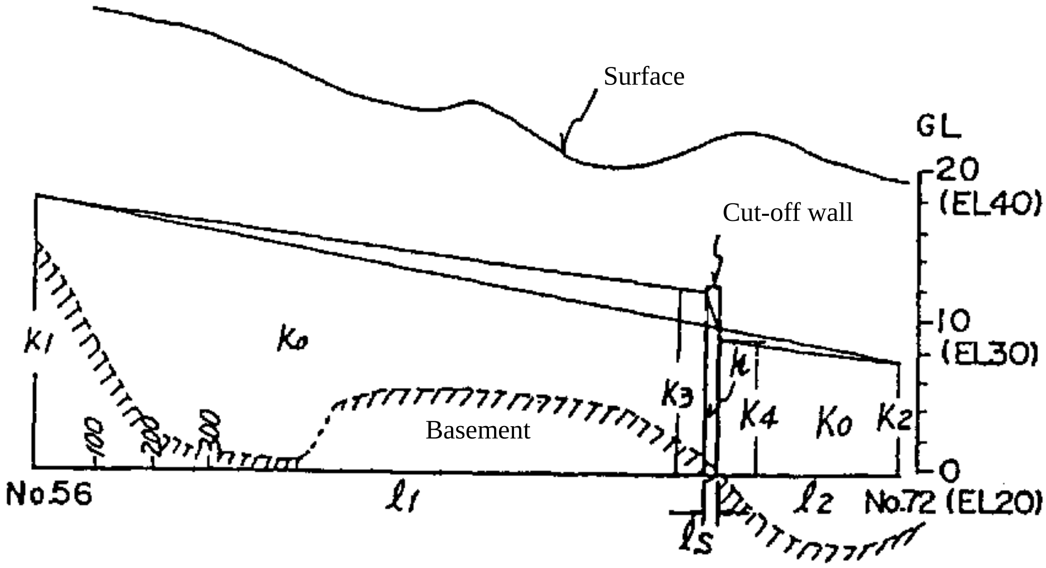
As Figure 5.2.1 shows, the flow rate per unit width Q of groundwater passing the cut-off wall can be calculated from k in the above formula and the hydraulic gradient ($(h_1 - h_2)/L_1$) can be calculated as follows:

$$Q = (h_1 - h_2)/((L_1 – L_2)/k_1 + L_2/k_2)$$

h_1: Groundwater level at the upstream of the cut-off wall, h_2: Groundwater level at the downstream of the cut-off wall

To keep Q within the tolerance, reduce k_2 or increase L_2. For the Minafuku subsurface dam, the design hydraulic conductivity of the cut-off wall was set to 5×10^{-5} cm/sec and the wall thickness to 5 m so that the groundwater flow to the downstream of the dam axis could be maintained at about 5% of the value without the subsurface dam.

Figure 5.2.1 Analytical Sectional View of the Minafuku Subsurface dam



For the cut-off walls of the Sunagawa and the Fukusato subsurface dams, the grouting method was initially planned. However, the cut-off walls were mostly constructed by the deep mixing method. This method was adopted because it could achieve the required precision in great-depth construction at low cost and the reduction of cut-off wall leakage successfully increased the available groundwater quantity. For both subsurface dams, because of financial reasons the grouting method was also used for some sections where the top surface of the basement is shallow.

When constructing a cut-off wall using several methods, the structure at each border of methods should be studied so as not to impair imperviousness. For the Sunagawa subsurface dam, both the deep mixing method and the grouting method were adopted for cut-off wall construction. The hydraulic conductivity differs between the diaphragm wall constructed by the deep mixing method and the wall constructed by the grouting method. Therefore, the diaphragm wall and the wall were overlapped by half the wall thickness of the grouting method (2.5 m) at the joint to ensure a full creep length.

5.2.3 Study of penetration

Where the cut-off wall contacts the basement, a necessary length of the cut-off wall is penetrated into the basement for the following purposes:

(1) Ensuring that the cut-off wall reaches the basement securely.

(2) Reducing groundwater of roundabout percolation at the lower, right, and left ends of the cut-off wall.

(3) Preventing the reservoir pressure from causing seepage failure where the cut-off wall contacts the basement.

The penetration length in (1) above is determined depending on the cut-off wall construction method and the accuracy of the basement depth check. Usually, a contour map of the top surface of the basement is created from the results of a boring survey and the top depth of the basement on the dam axis is estimated. If the boring survey density is low, the estimated top depth of the basement may contain some error. At cut-off wall construction, secure reach to the basement is possible if the construction method allows the confirmation of the end of the excavated part reaching the basement. If the construction method does not allow this confirmation, as in the deep mixing method, determine the construction depth by considering the error of the estimated top depth of the basement to ensure reach to the basement and adequate penetration length.

The penetration length related to (2) above is determined by experimentally calculating the permissible quantity of groundwater permeation (leakage). In particular, if there is a water level difference between the upstream and downstream of the cut-off wall, a great water pressure may work on the bottom of the cut-off wall and increase the leakage. To prevent this problem, penetrate the cut-off wall further, secure an adequate creep length, and reduce leakage. More specifically, the relationship between penetration length and leakage is clarified by two-dimensional cross-sectional seepage flow analysis and the design penetration length is determined from economic factors and permissible leakage.

If the basement contacting the cut-off wall is composed of unconsolidated sediments or the rock bed has cracks or fine grains in weak sections, water pressure may cause a seepage failure. This will form a water path, resulting in water leakage. If this is anticipated, forecast the permeation flow velocity and hydraulic gradient where the cut-off wall contacts the basement and compare them with the limit flow velocity and limit hydraulic gradient that may cause a seepage failure. From the results, determine the penetration length that can secure an adequate creep length. By studying the limit flow velocity and limit hydraulic gradient, the stability against a seepage failure is evaluated as follows:

(a) Judging the stability of the penetration part from the limit flow velocity

Set the groundwater flow velocity causing a seepage failure in the object ground as the limit flow velocity and compare it with the actual groundwater flow velocity to judge the stability against a seepage failure.

By infiltration analysis or other method, estimate the maximum groundwater flow velocity (apparent flow velocity) at the penetration part after cut-off wall construction. Then, calculate the actual flow velocity of groundwater through a gap as follows:

$Vs = V/\beta \qquad \beta = 1-(1-n)^{2/3}$

Vs: Actual flow velocity V: Apparent flow velocity β: Area porosity n: Pororsity

By assuming the representative grain size in the basement and cut-off wall at the penetration part, calculate the limit flow velocity as explained below. The representative grain size can be estimated from Creager's relationship between hydraulic conductivity and grain size.

Justin's formula $V^2 = (W \times g)/(A \times \gamma w) = 2/3 \times (G-1) \times d \times g$

- V: Limit flow velocity (cm/s)
- W: Soil particle weight in water (g/cm^3)
- g: Gravitational acceleration (cm/s^2)
- A: Grain area against water flow (cm^2)
- γw: Unit volume weight of water (g/cm^3)
- Gs: Specific gravity of soil particle
- d: Soil particle size (cm)

Koslova's formula $V = 0.26 \times d^2 \times (1+1000 \times d^2/D^2)$

- V: Limit flow velocity (cm/s)
- d: Noted particle size (mm)
- D: Mean diameter of medium (mm)

Evaluate the stability of the object section by comparing the actual flow velocity with the limit flow velocity above.

(b) Judging stability from the limit hydraulic gradient

Judge the stability of the permeation part by comparing the limit hydraulic gradient where the soil particles begin to move under water pressure and the actual hydraulic gradient acting on the penetration part.

The limit hydraulic gradient can be calculated as follows:

Sichart's formula $ic = 1/(1.5 \times \sqrt{k})$

Empirical formula of Chubu Power $ic = (1.671 \times 10^2/k) \times 0.623$

- ic: Limit hydraulic gradient
- Gs: True specific gravity of soil particle
- k: Hydraulic conductivity (cm/s)

Obtain the maximum flow velocity by infiltration analysis and calculate the hydraulic gradient as follows:

$i = V/k$ V: Maximum flow velocity (cm/s) k: Hydraulic conductivity (cm/s)

If the basement has a fault crossing the dam axis, it is necessary to study the possibility of leakage through the fracture zone. By checking the fault fracture zone and permeability, the penetration length must be extended as required.

For the Sunagawa subsurface dam, the penetration length of the cut-off wall was determined by leakage study. Table 5.2.2 shows the leakage at the Sunagawa subsurface dam found by infiltration analysis using the finite element method. Even when the penetration length was changed from 1 to 2 m, the leakage from the foundation did not lower significantly. The design penetration strength was set to 1 m by considering an increase of cut-off wall construction costs for the penetration length of 2 m.

Table 5.2.2 Assumed Leakage at the Sunagawa Subsurface dam (High Water Level)

Penetration Length	Leakage from Cut-off Wall	Leakage from Foundation	Remarks
1 m	1,486 m^3/day	64 m^3/day	Dam length: 1,835 m
2 m	1,496 m^3/day	46 m^3/day	

For the Komesu subsurface dam of saltwater infiltration prevention, the wall hydraulic conductivity, penetration length, and other cut-off wall dimensions were determined by saltwater infiltration analysis using hydraulic formulas and a model of the finite element method. The saltwater infiltration analysis is described below.

(a) Estimating the saltwater infiltration of the Komesu subsurface dam using hydraulic formulas

Based on the reservoir level in the reference year of intake plan found by water balance analysis, the daily saltwater infiltration was calculated by hydraulic formulas under the following conditions:

1) If the reservoir level becomes higher than the sea level (0 m), water leakage from the reservoir area to the downstream of the cut-off wall occurs. If the reservoir level becomes lower, saltwater infiltration into the reservoir area occurs.
2) The boundary between saltwater and fresh water is on the reservoir area side of the cut-off wall.
3) If the reservoir level becomes lower than the sea level (0 m), permeation from the cut-off wall to the reservoir area occurs instantaneously.
4) Even when the reservoir level is higher than the sea level (0 m), the permeation face of saltwater within the cut-off wall does not recede.
5) The permeation by difference in density and the viscosity of saltwater are not considered.

For calculation, the following hydraulic formulas were used (see Figure 5.2.2):

$$QA = kA \times (H_1^2 - H_2^2)/(2 \times l)$$
$$= kA \times (H_1 + H_2)/2 \times (H_1 - H_2)/l$$
= Hydraulic conductivity × Mean cross section of permeation × Hydraulic gradient

$$QA = qA \times L$$

qA: Permeation from cut-off wall per unit width, kA: Hydraulic conductivity of cut-off wall, H_1: Water level on the downstream side of cut-off wall

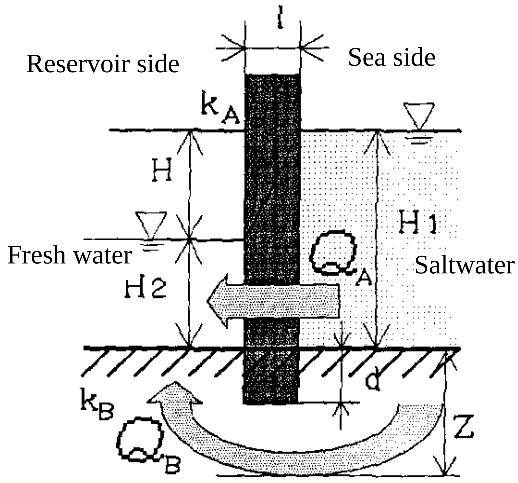
H_2: Reservoir level, l: Cut-off wall width, L: Permeation width (cut-off wall length), QA: Total permeation from cut-off wall

$$qB = 2.3 \times kB \times H/\pi \times \log(Z/d + \sqrt{(Z/d)^2 - 1})$$

$$QB = qB \times L$$

qB: Permeation from basement per unit width, kB: Hydraulic conductivity of basement, Z: Roundabout percolation width, H: Water level difference between upstream and downstream sides of cut-off wall (H_1-H_2), d: Penetration length, QB: Total permeation from basement

Figure 5.2.2 Analytical Sectional View of Saltwater Infiltration



The above formulas were calculated daily by assuming H_1 = 0 m (sea level), l = 0.5 m, L = 2,460 m, kB = 10^{-5} cm/sec, and Z = 30 m, varying kA (cut-off wall hydraulic conductivity) and d (penetration length), and giving H_2 in the water intake reference year for design (1971) by water balance calculation. Table 5.2.3 gives the results. Judging from the results, saltwater infiltration from the basement cannot be significantly reduced however much the penetration length of the cut-off wall into the basement is extended. This means that even a perfect cut-off wall cannot completely block saltwater infiltration into the basement.

Table 5.2.3 Calculated Permeations of the Komesu Subsurface dam (Reference year for Design: 1971)

Unit: m^3

Permeation from cut-off wall	Hydraulic conductivity of cut-off wall (kA)	Leakage from cut-off wall		Infiltration through cut-off wall		Balance
		Annual (A)	Daily maximum	Annual (B)	Daily maximum	A-B
	10^{-5} cm/sec	1,051,000	6,150	1,056,000	13,555	5,000
	10^{-6} cm/sec	105,100	615	105,600	1,356	500
	10^{-7} cm/sec	10,500	62	10,560	136	60
Permeation from basement	Penetration length of cut-off wall (d)	Leakage from basement		Infiltration through basement		Balance
		Annual (A)	Daily maximum	Annual (B)	Daily maximum	A-B
	1 m	19,200	118	23,600	324	4,400
	2 m	16,000	93	19,600	269	3,600
	5 m	11,600	68	14,300	196	2,700
	10 m	8,300	48	10,100	140	1,800

(b) Estimating saltwater infiltration from the Komesu subsurface dam using a model of the finite element method

By infiltration analysis using the finite element method, saltwater infiltration from the cut-off wall and basement into the reservoir area was studied. The basement of the Komesu subsurface dam is composed of Chinen arenite of slightly high permeability and Shimajiri pelite of low permeability. For analysis, the permeability differences of basement were also reflected, as shown in Table 5.2.4.

Table 5.2.4 Conditions of Analyzing the Komesu Subsurface dam with a Model of the Finite Element Method

Item	Setting	
Hydraulic conductivity of basement	Arenite (upper layer (weathered)) Arenite (lower layer (fresh)) Pelite (upper (weathered)) Pelite (lower (fresh))	1.0×10^{-4} cm/sec 2.0×10^{-5} cm/sec 2.0×10^{-6} cm/sec 1.0×10^{-7} cm/sec
Hydraulic conductivity of wall	1.0×10^{-6} cm/sec	
Wall thickness	0.5 m	

Figure 5.2.3 shows an example of infiltration analysis and Table 5.2.5 shows the results of analysis. When the cut-off wall thickness is 0.5 m and the hydraulic conductivity is 1.0×10^{-6} cm/sec, the permeation of saltwater into the reservoir area in the water intake reference year for design (dry year) is 116,000 to 137,000 m^3. If the hydraulic conductivity of the cut-off wall is made one order smaller to 1.0×10^{-7} cm/sec, saltwater permeation from the cut-off wall becomes about one-tenth of that in Table 5.2.5 (about 9,000 m^3/year) and permeation from the foundation exceeds that from the cut-off wall.

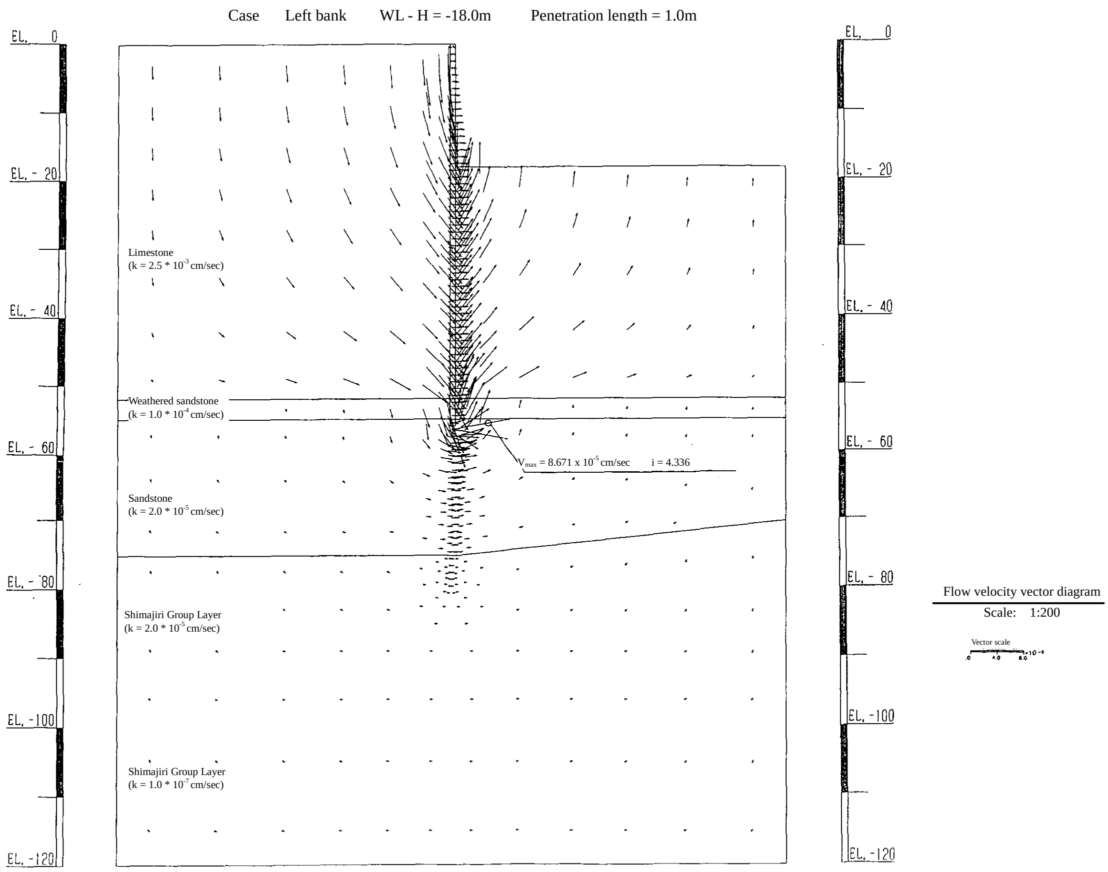
The saltwater permeation of 116,000 to 137,000 m^3 is about 3 or 4% of the gross reservoir capacity of 3,475,000 m^3. If this saltwater is completely mixed with fresh water in the reservoir, the salinity concentration becomes about 400 mg/lit. However, even lower salinity concentration can be estimated because water permeates from the reservoir area into the sea in many years, the intake facilities installed more than several tens of meters away from the dam axis do not take in much saltwater, and the water from the Komesu subsurface dam is mixed with water from other sources and its salinity drops due to dilution.

By considering the results of saltwater infiltration analysis and the efficiency and economy of the cut-off wall, the design hydraulic conductivity was set to 1.0×10^{-6} cm/sec and the thickness to 0.5 m for the wall of the Komesu subsurface dam. Regarding the penetration part, the arenite or pelite layer of 2.0×10^{-5} cm/sec or less in hydraulic conductivity was set as a non-permeable basement and a cut-off wall was constructed from its top surface to one meter deep by considering imperviousness and construction efficiency.

Table 5.2.5 Calculated Permeations of the Komesu Subsurface dam (Reference Year for Design (1971))

Penetration Length of Cut-off Wall	Saltwater Permeation from Cut-off Wall (m^3/year)	Saltwater Permeation from Basement (m^3/year)	Total (m^3/year)
Penetration length: 1 m	97,700	39,600	137,300
Penetration length: 2 m	99,500	29,100	128,600
Penetration into pelite layer (Total arenite layer cut-off)	110,900	4,600	115,500

Figure 5.2.3 Example of Infiltration Analysis by the Finite Element Method (Flow Velocity Vector Diagram)



5.2.4 Dam height

The dam height is determined by considering the necessary reservoir capacity and the necessity of drainage facility installation as explained below.

(1) Securing a reservoir capacity that satisfies the water source plan

Raising the dam height increases the reservoir capacity. This also has an advantage of making intake easy because the reservoir level becomes high.

(2) Preventing damage by a groundwater level rise in the reservoir area

Cut-off wall construction blocks the groundwater flow and usually raises the reservoir level. It is necessary to drain surplus groundwater so that an excess rise of the reservoir level will not affect the land use on the surface. To allow surplus groundwater to overflow from the dam crest to the downstream area under no special control, it is preferable to set an appropriate dam height and secure an adequate overflow freeboard. If it is necessary to raise the dam height for securing an adequate reservoir capacity or surplus groundwater cannot be drained by dam crest overflow because the overflow ground has low permeability, drainage facilities should be installed in the reservoir area.

(3) Making the construction economical by considering the entire subsurface dam

For economical construction, weigh the extra cut-off wall construction costs and damage facility installation costs against the advantages of raising the dam height.

5.2.5 Design strength of cut-off wall

A cut-off wall for a subsurface dam is usually installed underground between ground layers. Therefore, excessive strength is not necessary for self-standing. As a load, the cut-off wall receives hydrostatic pressure that corresponds to the water level difference between the upstream and downstream of the cut-off wall. Note that this pressure may produce a compressive stress, flow cut-off wall materials away, and cause hydraulic destruction.

For the Fukusato subsurface dam, the bending moment and shearing stress may be ignored for the hydrostatic pressure and only the compressive stress should be considered because the cut-off wall is protected from deformation in the upstream-downstream direction by a limestone rock bed of 10 to 30 N/mm^2 in unconfined compression strength. Regarding the Fukusato subsurface dam, if hydrostatic pressure up to 52 m is assumed to act on the cut-off wall, the maximum compressive stress on the cut-off wall will be 0.5 N/mm^2. To withstand this load, the design strength of the cut-off wall was set to about 1 N/mm^2.

The wall needs great strength and durability near the top end where the groundwater overflows because the groundwater flows most severely there. The Sunagawa subsurface dam and others are reinforced with concrete of sufficient strength near the top end to control the dam height and improve the durability. Since a cut-off wall quakes together with the surrounding ground during an earthquake, the possibility of it being damaged is considered to be low. If an earthquake occurs, however, the cut-off wall should be surveyed for damage and water leakage by investigating the form of the groundwater surface near the cut-off wall.

If there are limestone caves or other cavities with the cut-off wall in between, the cut-off wall requires enough strength to stand alone and withstand shearing.

5.2.6 Determination of cut-off wall construction method

(1) Conditions of selecting cut-off wall construction method

Determine a cut-off wall construction method by thoroughly considering the conditions of construction, economy, and other items listed in Table 5.2.6. Table 5.2.7 introduces cut-off wall construction for subsurface dams and Table 5.2.8 compares main cut-off wall construction methods.

Table 5.2.6 Study Items for Selecting Cut-off Wall Construction Method

Study Item	Description
Dimensions of cut-off wall	The wall thickness and permeability are determined by the machine scale and wall materials.
Construction depth	It is preferable to construct a cut-off wall vertically for low cost and accurate cut-off. A very deep subsurface dam requires high vertical construction precision because deviation from the vertical line grows as the depth increases. As the depth increases, the construction machines receive greater loads and the excavation efficiency declines. Therefore, machines having extra capacity should be selected according to the depth.
Current groundwater level	The groundwater level affects the conditions of eliminating excavated soil and the works. If the groundwater level is low and ground permeability is high, it becomes difficult to eliminate soil. In addition, the construction methods may be limited because mud water makes the walls of holes unstable.
Permeability of overflow ground	When allowing surplus water to overflow from the reservoir area over the cut-off wall, the permeability of the ground around the overflow should be maintained at cut-off wall construction.
Soil characteristics	Stable walls of holes are a requirement for safe and efficient construction. Especially for the rearrangement method, self-standing walls of holes are a prerequisite. In addition, the ground hardness affects the excavation efficiency. If the quality cut-off wall depends on the type of ground, the mixing of wall materials and the construction method may require considerations. This is especially necessary for inhomogeneous ground.
Ambient environment	Environmental influences around the construction site should be considered. Select an appropriate construction method according to the conditions of transporting construction machines, the stability of the ground on the construction site, and noises, vibrations, and water pollution at construction.
Machines and materials	Clarify how construction machines and materials will be purchased and transported. If necessary machines or materials are not available in the country, their transportation will take cost and time.
Economy	Select cut-off wall construction methods that satisfy the above conditions and are technically feasible. Then, determine a method by comparing costs.

When using a cut-off wall that has never been used under the field conditions of the scheduled point, experimental work before full construction work is preferable for verifying the applicability of the cut-off wall construction method and studying its procedures.

Table 5.2.7 Cut-off Wall Construction for Subsurface dams

Type	Name	Outline	Remarks	Wall Thickness	Example of Subsurface dam
Open-cut	Open-cut method	The ground is dug down to the bottom line of the dam manually or by using a power shovel. The wall is constructed with impervious materials, such as clay, concrete, brick, and masonry, and then the ground is backfilled.	Applicable only when the construction depth is shallow. Construction should be done when the groundwater level is low.	Several meters	Small-scale subsurface dams in North Africa and South India
Soil improvement	Grouting (injection)	Cement, clay, or other hardening materials are jetted from boreholes by ultra high-pressure air or water to reduce the ground permeability. This method can be classified into the stage grouting method and the twin-pipe grouting method.	A gravel ground makes it difficult to control the injection range and may fail to overlap injection areas. If the depth is deeper than 50 m, the hole may be bent and the cut-off performance may be lowered. For the improvement of permeation, high-density work is necessary. A finishing check is necessary.	Several meters	Kabashima, Tengakuma, Sunagawa, Fukusato, Minafuku, and Yonesu
	Jet grouting	Chemical liquids or cement-type hardening materials are jetted from boreholes by ultra high-pressure air or water to destroy the ground organization and mix or replace the soil with hardening materials.	Difficult to apply to bedrock. This method may not be applicable to constructing a wall on a gravel basement. If the ratio of gravel is 30% or more, a hole may be bent and makes the wall not continuous. The back faces of boulder stone and cobble stone are difficult to improve.	1.0 to several meters	Long he (China) Long kou (China)
Impervious materials erection	Thin cut-off wall	A narrow groove is excavated under the ground by using a rotary excavator or a chainsaw-type excavator and rubber or steel sheets or cement-type materials are inserted and placed.	The groove wall should be self-standing. For rubber sheets, inter-sheet bonding should be carefully considered.	Up to 0.2 meter	Kikai (test)
	Steel sheet piling	Steel sheets are continuously driven in with a vibro-hammer to construct a dam. If the ground is hard, water jet is also used. The sheets are engaged securely and sealed with grouts and expansion cut-off materials.	Suitable for a comparatively shallow construction depth and ground with 30 or smaller N value. This method may be difficult to apply to a gravel layer. To ensure an overflow, digging down to the levee crown or separate drainage ground facilities are necessary.	Up to 0.5 meter	Kikai (test) Senbaru (planned)
Subsurface diaphragm wall	Bucket excavation	A groove is excavated by using a bucket excavator and concrete or mud water hardening materials are used for replacement.	Requires a self-standing groove wall and cannot be used to excavate a rock bed harder than soft rock. Construction deeper than 100 m may be possible.	0.4 to 2.5 meters	Jojin, Waita, and Kikai (under test)
	Horizontal multi-axis excavation	A groove is dug by using two opposed horizontal-axis rotary cutters. Slime is eliminated by circulating mud water and is replaced with concrete or other hardening materials.	Requires a self-standing groove wall. This method cannot be used to excavate a rock bed harder than soft rock. Construction deeper than 100 m may be possible. Requires a self-standing groove wall. The precision control technology has been established. If mud water does not circulate, auxiliary work is necessary. This method has been used for work deeper than 100 m. Bedrock up to about 50 MN/m^2 can be excavated.	0.3 to 3.2 meters	Yonesu (test)
	Vertical multi-axis excavation	A groove is excavated by using several vertical-axis rotary bits. Slime is eliminated by circulating mud water and is replaced with concrete or other hardening materials.	Based on a self-standing groove wall. The precision control technology has been established. If mud water does not circulate, auxiliary work is necessary. This method has been used for work deeper than 100 m.	0.5 to 1.2 meters	Sekkan
Cast-in-place diaphragm method	Large-diameter drilling	A casing with a bit embedded at the tip is oscillated for excavating. The excavated soil is eliminated by using a hammer glove. While the casing is being extracted, mortar is filled in.	Allowing construction deeper than 100 m. This method can be used to excavate even soft rocks and cobblestones.	0.8 to 1.5 meters	Kikai (test) Yonesu (test)
	Cast-in-place deep mixing	The ground is mechanically excavated and crushed with a tri-axial auger. While the soil is being kneaded with cement-type hardening materials, a continuous soil cement wall is constructed.	Cavity processing technology already established. Bedrock of up to about 50 MN/m^2 can be excavated. This method can be used to excavate up to about 70 m deep. If the depth increases, hole bending occurs. This necessitates additional work to ensure a continuous wall.	0.5m	Sunagawa, Fukusato, Kanjin, Yonesu, Giiza, Kikai, Yokatsu, Nakajima, and Kamiko

Table 5.2.8 Comparison of Main Cut-off Wall Construction Methods

	Open-cut	Grouting	Steel Sheet Piling	Diaphragm Wall
Wall materials	Clay, cement, and other. The optimum water content should be determined for full consolidation.	Liquid grout of cement-type hardening materials or chemical liquid and other. The optimum mixture of a liquid grout and the injection pressure should be determined according to the ground conditions.	Steel or concrete sheets and other	Cement-type hardening materials, or a mixture of cement-type hardening materials and ground components (soil cement). The optimum mixture of a liquid grout should be determined according to the properties of the object ground.
Wall endurance	Semi-permanent. If clay is used, however, the wall should be thickened to prevent cracking by drying.	Semi-permanent. If a low-quality grout is used, however, weathering may make the wall more permeable.	If steel sheets are used, full measures against corrosion are necessary.	Semi-permanent. To withstand the water pressure, certain strength is necessary.
Object ground	Unconsolidated ground to strongly weathered bedrock	Unconsolidated ground to strongly weathered bedrock. To make unconsolidated ground more impermeable, twin-pipe grouting may be necessary.	Unconsolidated ground of mainly clay and sand. If the ground is hard, water jetting or other special methods are necessary.	Unconsolidated ground to strongly weathered bedrock. Some machines can excavate even hard bedrock.
Groundwater conditions	Work below the groundwater level requires drainage. In addition, the excavation slope becomes unstable and the work becomes difficult.	If the velocity of groundwater flow is especially high, the liquid grout may flow away to make cut-off difficult.	No special influences under groundwater.	If the velocity of groundwater is especially high, the excavation mud water and hardening materials may flow away and make the work difficult.
Depth	Not deeper than several tens of meters. A depth increase lowers the accuracy of impermeability and creates an economic disadvantage.	Usually suitable for construction within about 40 m deep. If the depth is greater, hole bending may occur, which would lower the accuracy of impermeability.	Suitable for construction at a shallow depth, although it has been used for construction up to about 40 m deep.	Available for construction deeper than 100 m. If the depth increases, hole bending may occur and the wall may not be continuous.
Accuracy of impermeability	Using clay, concrete, or other impervious materials as the wall materials ensures accurate impermeability.	Inferior to other methods in accuracy of impermeability. The limit of improving the impermeability is not more than in the order of 10^{-5} cm/s. For higher impermeability, it is necessary not only to suppress hole bending but also to increase injection hole rows and to thicken the wall.	The sheets are impermeable but their joints require dewatering.	Cement-type hardening materials can be used as wall materials to secure high impermeability. If hole bending occurs at excavation and wall continuity cannot be secured, additional work is necessary.
Construction of overflow section	Backfilling with pervious materials ensures accurate work.	Cap grouting is necessary to prevent grout leakage to the overflow section.	It is difficult to secure an overflow section. Therefore, a work yard should be prepared after digging to backfill the ground with pervious materials or separate drainage facilities should be constructed.	An overflow section can be secured by devising the construction method. If the groove wall of the overflow section is not self-standing, however, a work yard should be prepared after digging to backfill the ground with pervious materials, or separate drainage facilities should be constructed.
Excavation machinery	No special excavation machines are necessary. Human power or general-purpose excavation machines are sufficient.	Boring machines and injection plants are necessary but the machine scales are comparatively small.	A vibro-hammer and other dedicated machines are necessary but the machine scales are smaller than those for the diaphragm wall method.	Dedicated excavation machines are necessary. These machines are often large, and transportation and assembling is costly and time-consuming.
Temporary facilities	An area is necessary for storing surplus soil after excavation.	Large-scale temporary facilities are necessary only if the slope is steep.	A stable work yard is necessary to ensure machine stability.	Since position control and stability of the excavation machines affect the precision of excavation, the work yard including the groove wall should be stable. The temporary facilities are of comparatively large scales.
Work scale	Suitable for small-scale work	Arbitrary	Arbitrary	Suitable for large-scale work

(2) Open-cut method

If the top surface of the basement is shallow, a cut-off wall for the subsurface dam can be constructed by digging the ground from the surface and backfilling the ground with low-permeability materials. Subsurface dams have a long history of construction by the open-cut method and have been constructed in North America, South India, and other locations. Open-cut method does not require special machines or materials. If the labor budget is low, a subsurface dam can be constructed by human power at low costs.

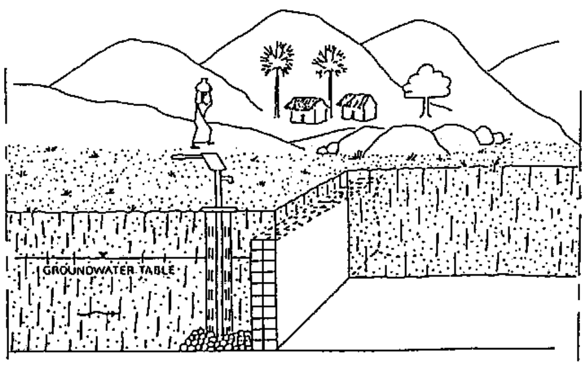
Many subsurface dams constructed by the open-cut method are up to about 10 m deep. As the depth of the cut-off wall increases, more excavation becomes necessary and increases construction costs. A cut slope at excavation should have a stable gradient according to the consolidation of earth, the grain size, and other. If the earth is not consolidated and the excavation depth is shallow, the preferable gradient of cut slope is 1:1.0 to 1:1.2. If the excavation depth is deep or exceeds the groundwater surface, the gradient of cut slope should be further reduced to ensure safety. In addition, it is preferable to create a small stage at every 5 m of excavation.

Construction below the groundwater surface should be avoided whenever possible because drainage becomes necessary and the moistened earth easily collapses. In an area where the dry and rainy seasons are clearly separate, the construction work should be done in the dry season when the groundwater level is low. If construction below the groundwater surface is inevitable, spring water treatment becomes necessary. This also necessitates slope monitoring to ensure safety during construction work.

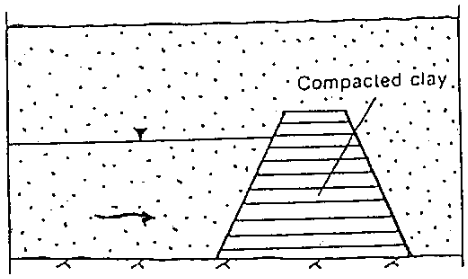
The existing subsurface dams constructed by the open-cut method use consolidated cohesive soil, concrete, plastered bricks, piled stones, and other as impervious materials. Cohesive soil can reduce costs if available near the cut-off wall planned site. As impervious materials, clay should be fully consolidated by securing the optimum water content. In addition, the cut-off wall should be thick enough to retain moisture for preventing cracking in the dry season.

An excavated site is usually backfilled with the original soil, excluding the cut-off section. At backfilling, the earth should be fully consolidated while maintaining permeability at the overflow section. Figure 5.2.4 shows a sectional view of the open-cut method.

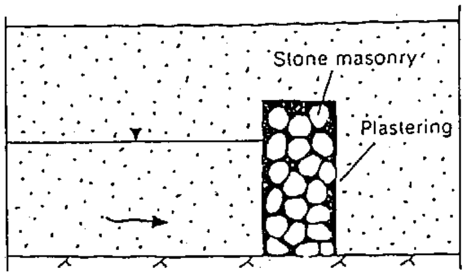
Figure 5.2.4 Sectional View of the Open-cut Method



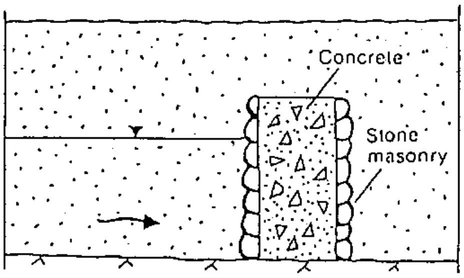
General principle of a sub-surface dam.



Clay dike.



Stone masonry dam.



Concrete dam.

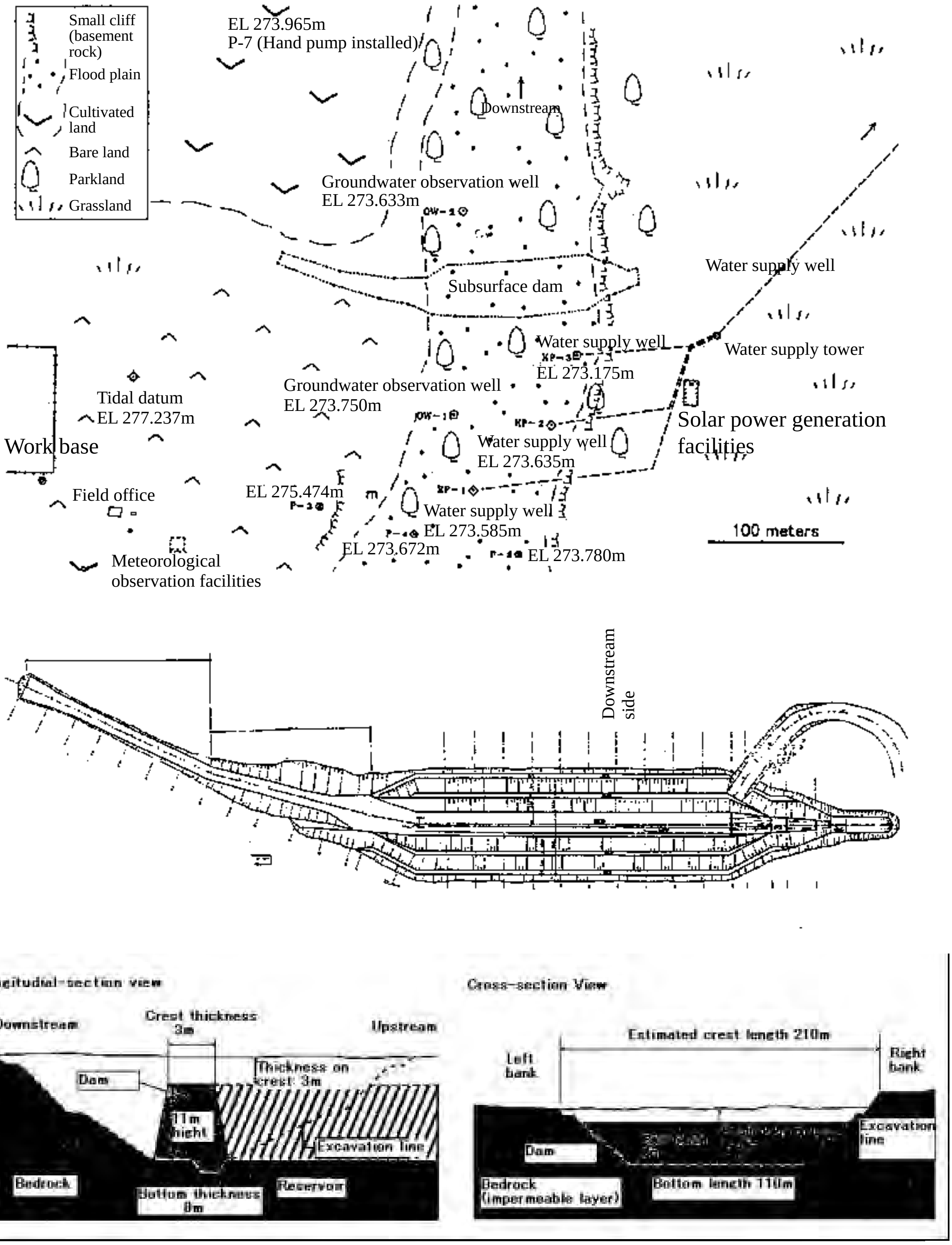
Combining the open-cut method with another cut-off wall construction method may make more economical construction possible. For example, the open-cut method may be applied above the groundwater surface and the grouting or diaphragm wall method below the groundwater surface. This will reduce the depth of construction by grouting or diaphragm wall method to improve the construction precision and to reduce costly machine excavation and the total construction costs. In addition, the permeability around the overflow section can be improved by backfilling the excavated ground with permeable materials.

In Nare Village, Namentenga, Burkina Faso, an afflux-type subsurface dam was constructed by the open-cut method on the ODA budget from Japan. Table 5.2.9 lists the design dimensions and Figure 5.2.5 shows a plane and sectional view.

Table 5.2.9 Dimensions of the Nare Subsurface dam in Burkina Faso

Item	Outline
Purpose of subsurface dam	To construct a subsurface dam in a subsurface valley, an old river buried by river sediments, for using the stored groundwater in the dry season
Geology	Aquifer: Gravels, sand, and silt to clay Basement rock: Granite, etc.
Reservoir area	Depth: 14 km, width: 180 m, aquifer thickness: 8.5 m
Reservoir capacity	Target capacity: 800,000 m^3
Scale of cut-off wall	Crest length: 210 m (bottom length: 110 m), height: 8 m, thickness: 3 m (bottom thickness: 8 m), overflow freeboard: 3 m
Cut-off wall materials and consolidation method	Rolled compaction of cohesive soil distributed around the surface near the dam axis by using heavy machinery
Contents of work	1. Excavation Machine excavation by backhoe and bulldozer Finishing excavation by human power and cleaning of the finally excavated ground Earth excavation: 51,213 m^3 Rock excavation: 4,277 m^3 2. Rolled compaction and backfilling High-density fill (main body): 7,144 m^3 Medium-density fill (downstream backfilling on main body): 26,662 m^3 Low-density fill (overflow backfilling): 21,814 m^3 3. Quality control standard Rolled compaction of high-density fill: Six round trips of heavy machine for rolled compaction Rolled compaction of medium-density fill: Three round trips of heavy machine for rolled compaction Rolled compaction of low-density fill: Three round trips of heavy machine for rolled compaction Water content before fill: High-density fill Optimum water content -1.0% - +1.5% Medium- or low-density fill No standard Post-fill field test: Dry density 90% or more of maximum density 3 points/layer Field permeability test $\times 10^{-5}$cm/sec max 1 point/4 layers 4. Results of field control tests on main body fill Optimum water content : 10.09 to 17.30% (130 points total) Compaction density : 1.75 to 2.025 t/m^3 (130 points total) Hydraulic conductivity : 2.4×10^{-6} to 4.5×10^{-8} cm/sec (38 points total)

Figure 5.2.5 Plane and Sectional View of the Nare Subsurface dam



In the Diplo District and Principal District, Pangasinan, the Philippines, intake facilities consisting of groundwater-impervious walls and collecting underdrains were constructed by the open-cut method as part of a project to recover buried irrigation facilities, with gratuitous financial cooperation from Japan.

The intake of groundwater (riverbed water) from riverbed sediments through underdrains was adopted as a method allowing the intake of riverbed water in the dry season of surface water shortage and having a stable structure free of maintenance. To ensure stable intake, a groundwater-impervious wall reaching from the current riverbed surface to the basement layer was constructed at the downstream end of an underdrain as a subsurface dam. The groundwater-impervious wall has a surface intake port with holes to distribute surface water also to the surface water channel in the rainy season.

To serve also as groundsill works having an upstream-downstream head of about 1 m, the groundwater-impervious wall was made of reinforced concrete with members thick enough to withstand a head of even about 3 m on the downstream side. In addition, gabion groundsill works were installed on the downstream side of the impervious wall to stabilize the riverbed and gut. The groundwater-impervious wall has spillway on the surface to safely discharge surface water in the flood season.

At the construction of the groundwater-impervious wall, the riverbed sediments were dug until the reinforced concrete basement layer was constructed, and the ground was backfilled. Table 5.2.10 and Figures 5.2.6 and 5.2.7 introduce the facilities.

Table 5.2.10 Outline of Irrigation Facilities in the Diplo and Principal Districts in the Philippines

District	Facilities	Dimensions of Facilities
Diplo	Groundwater impervious wall	Dam length: 188 m, buried depth: 18 m, wall thickness: 80 cm Accessory facilities - Spillway (width: 80 m), surface intake works: 1, groundsill: 3
	Groundwater collecting underdrain	Reinforced plastic pipe with hole (pipe diameter: 60 cm) 20 m × 35
Principal	Groundwater-impervious wall	Dam length: 207 m, buried depth: 12 m, wall thickness: 80 cm Accessory facilities - Spillway (width: 120 m), surface intake works: 1, ground sill: 2
	Groundwater collecting underdrain	Reinforced plastic pipe with hole (pipe diameter: 80 cm) 24 m × 35

Figure 5.2.6 Plane of Facilities in the Diplo District

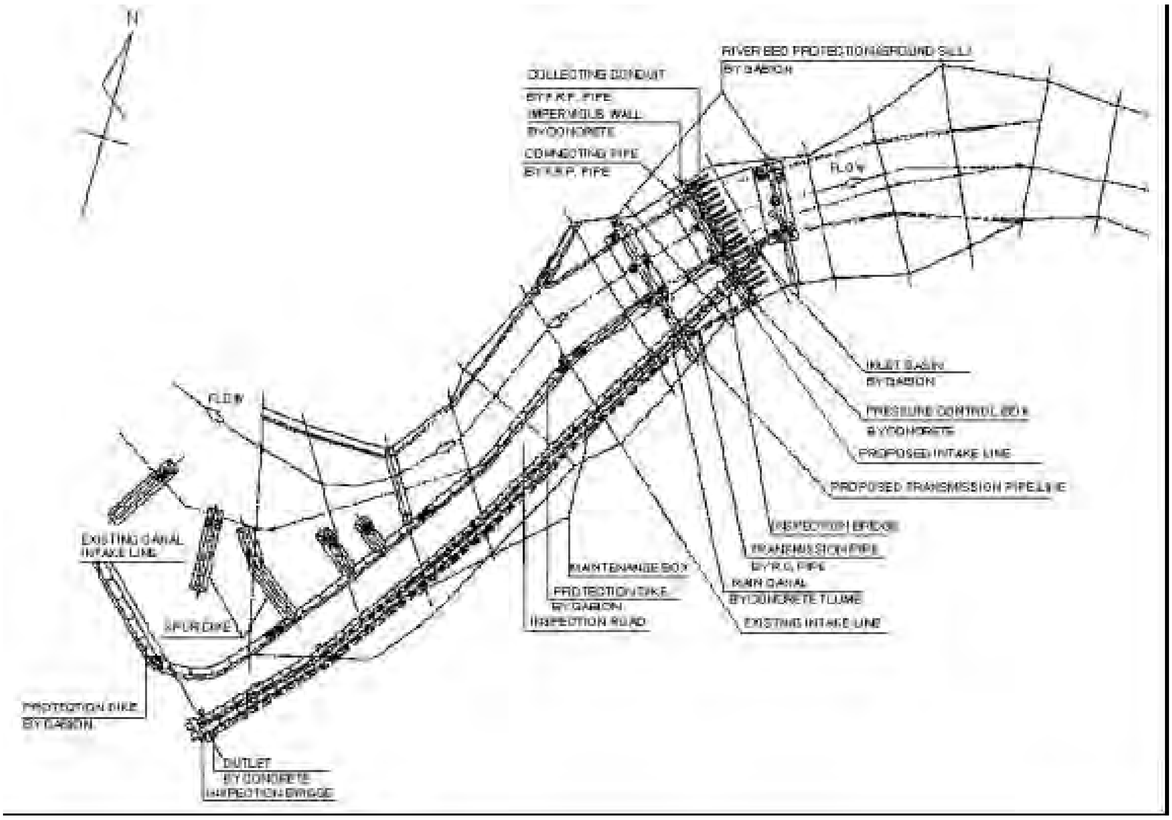
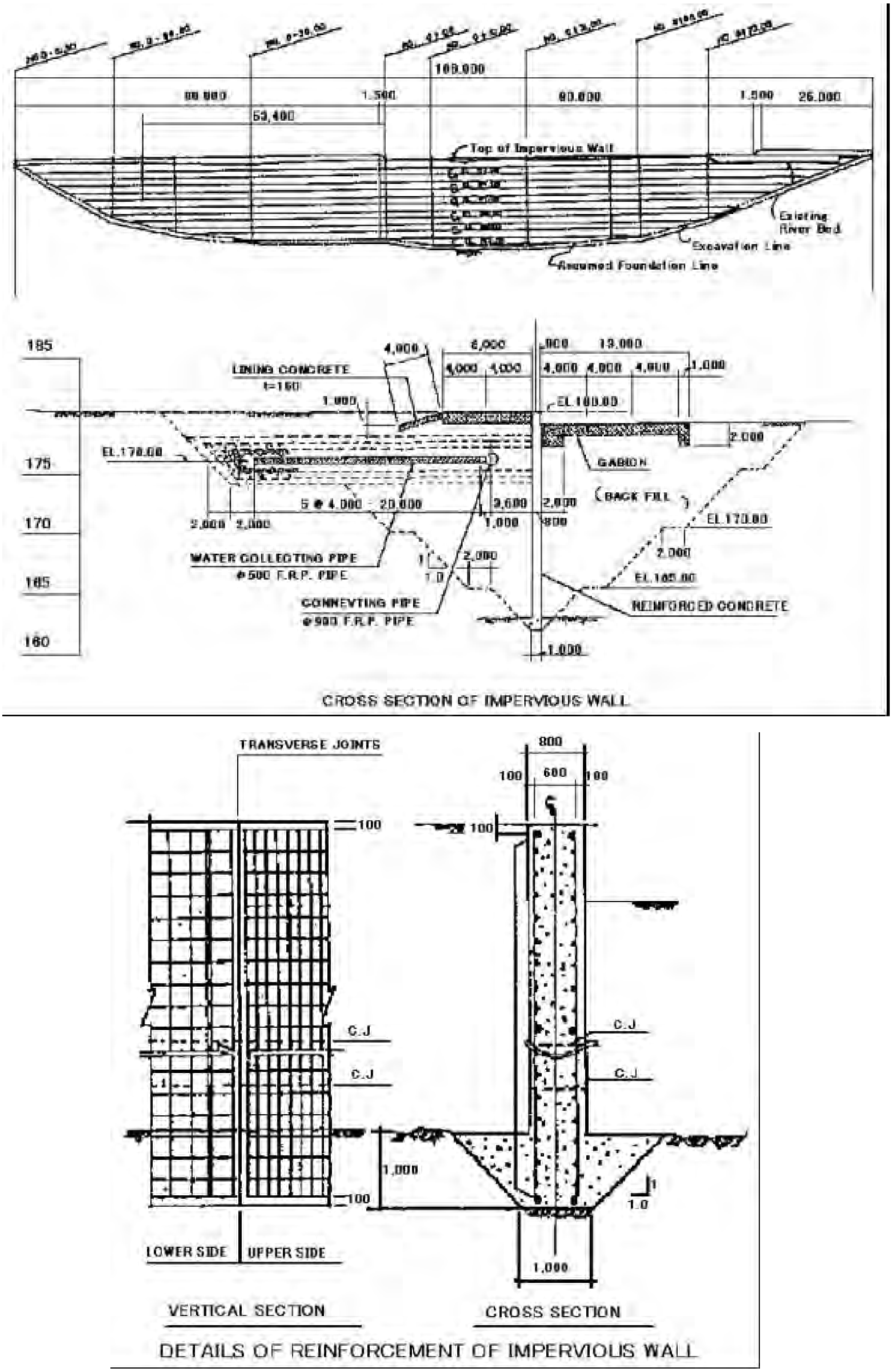


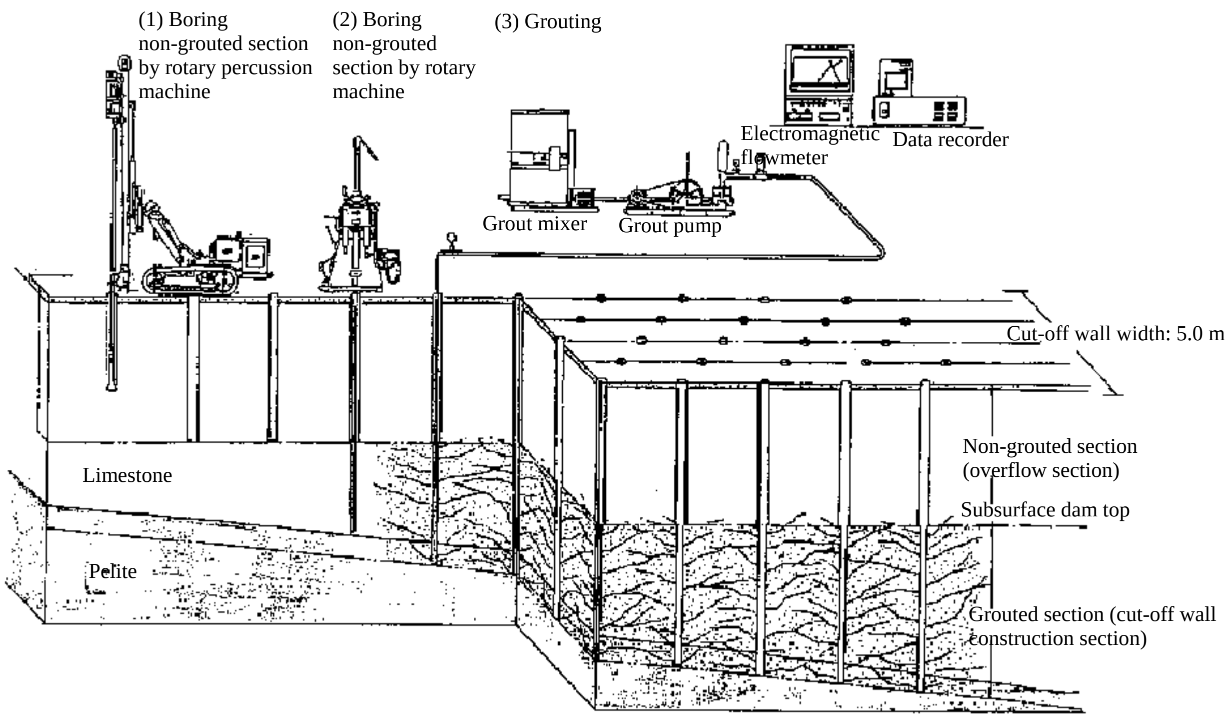
Figure 5.2.7 Sectional View of Facilities in the Diplo Region



(3) Grouting method

The grouting method is to inject cement and other hardening materials through boreholes into ground cavities by pressure to reduce the ground permeability for constructing a cut-off wall. Figure 5.2.8 shows the concept of construction using the grouting method.

Figure 5.2.8 Concept of Construction Using the Grouting Method



The grouting method has the advantage that large construction machines are not necessary and the construction costs are comparatively low. This method is generally considered not to reduce the hydraulic conductivity of ground lower than the 10^{-5}cm/sec order and often cannot be expected for great permeability improvement. If the object ground has complicated composition, an inhomogeneous cut-off wall of dispersive permeability may be constructed. If the construction depth becomes great, the boreholes are bent excessively and continuous imperviousness becomes difficult to secure.

At the design of a cut-off wall by the grouting method, it is necessary not only to clarify the above problems but also to check by test construction the range of hydraulic conductivity that can be improved. If the permeability of ground cannot be adequately improved due to great depth, increase the number of grouting holes and make the wall sufficiently thick.

Without controlling the grouting routes, a cut-off wall may not be constructed as designed. To prevent this problem, change the blending of the liquid grout by the hole arrangement or adjust the setting rate of the liquid grout to ensure that it will scatter only on the planned cut-off wall construction site.

By process, the grouting method can be divided into several types as listed in Table 5.2.11.

Table 5.2.11 Outline of Major Grouting Types

Type	Outline
Rod method	After boring to the final planned depth, a rod is lowered to the bottom of the hole. While grouting from the top, the rod is lifted sequentially as the grouting pressure increases.
Stage method	Boring and grouting are proceeded with alternately from the highest stage to the lowest one.
Packer method	After boring to the final planned depth, a packer is set at the lowest stage and the stage is grouted first. Then the upper stages are grouted sequentially.
Twin-pipe double packer method	After boring to the final planned depth, an external pipe with grouting tube is installed in the hole and an internal with double packer is inserted into the external pipe for grouting into each grouting valve.

The cut-off wall for the Sunagawa subsurface dam was partially constructed by the grouting method. At the design of dam construction by grouting method, the planned dam axis was partially constructed by various types of grouting to study the grouting method, grouting pattern, and blending of grout. Consequently, the stage method using ordinary Portland cement was adopted. Figure 5.2.9 and Table 5.2.12 introduce the dimensions.

Figure 5.2.9 Arrangement of Grouting Holes for the Sunagawa Subsurface dam

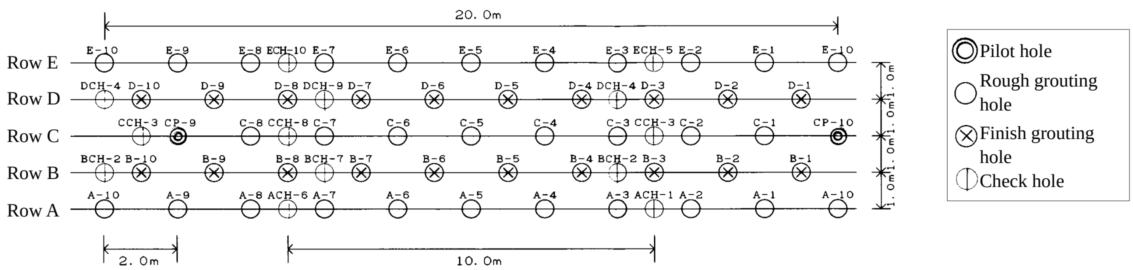


Table 5.2.12 Grouting Dimensions for the Sunagawa Subsurface dam

Item	Dimensions
Grouting row type	1. Gap grouting (Stage 0 grouting) One meter from the levee crown to prevent cement milk leaking to the overflow section 2. Rough grouting Upstream and downstream rows (A and E) and central row (C) among the five grouting rows 3. Finish grouting Intermediate rows (B and D) between the rough grouting holes among the five grouting rows
Construction order of grouting rows	Rows A and E (Stage 0)→Row C (Stage 0)→Rows B and D (Stage 0)→Rows A and E (Stage 1 to 2)→Row C (Stage 1 to 2)→Rows B and D (Stage 1 to 2)
Depth of grouting Staging	EL. 32 – 31 m : Stage 0 (Grouting section length: 1 m) EL. 31 – 28 m : Stage 1 (Grouting section length: 1 – 3 m) EL. 28 m : Stage 2 (Grouting section length: 1 – 3 m)
Blending of grout	Rough grouting : Cement (W/C = 6/1, 4/1, 2/1, 1/1) Finish grouting : Cement and bentonite (W/(C+B) = 8/1, 6/1, 4/1, 2/1, 1/1)
Goal of improvement	Mean hydraulic conductivity in the transverse direction of cut-off wall: 5×10^{-5} cm/sec max
Grouting pressure	Stage 0 : 0.5 kg/cm^2 Rough grouting : 1.0 kg/cm^2 Finish grouting : 3.0 kg/cm^2
Grouting speed	20 liters/min/stage

For cut-off wall construction, both the grouting method and the deep mixing method were used at the Sunagawa and the Fukusato subsurface dams. For a cut-off wall of the wall ratio (cut-off wall height/construction height (depth from the surface to the basement of the cut-off wall) × 100 (%)) of 10 to 30%, the grouting method is more economical than the deep mixing method. Therefore, the grouting method is used for wings and counter dams where the wall ratio is small.

The stage method generally is applicable to ground where borehole walls do not collapse and the grouting limit pressure is high enough. The twin-pipe double packer method should be discussed for ground of the following conditions if the stage method does not seem to sufficiently improve the ground even by long grouting.

(1) Packers do not work well.
(2) Hole wall cannot stand alone.
(3) Even when the grouting speed is reduced, surface and packer leaks occur frequently.
(4) Some layers can be improved but grouting is not applicable to specific layers.

The twin-pipe double packer method has the following characteristics:

(1) Repetitive and compound grouting from the same valve (Reg-routing at an arbitrary depth allowed)
(2) Applicable to soft or gravel ground where a bare hole wall cannot stand alone
(3) High construction efficiency because sleeve pipe installation and grouting are proceeded with

separately

(4) Higher construction cost than the stage and grouting methods

Figures 5.2.10 and 5.2.11 shows an outline of the twin-pipe double packer method.

Figure 5.2.10 Basic System of the Twin-pipe Double Packer Method

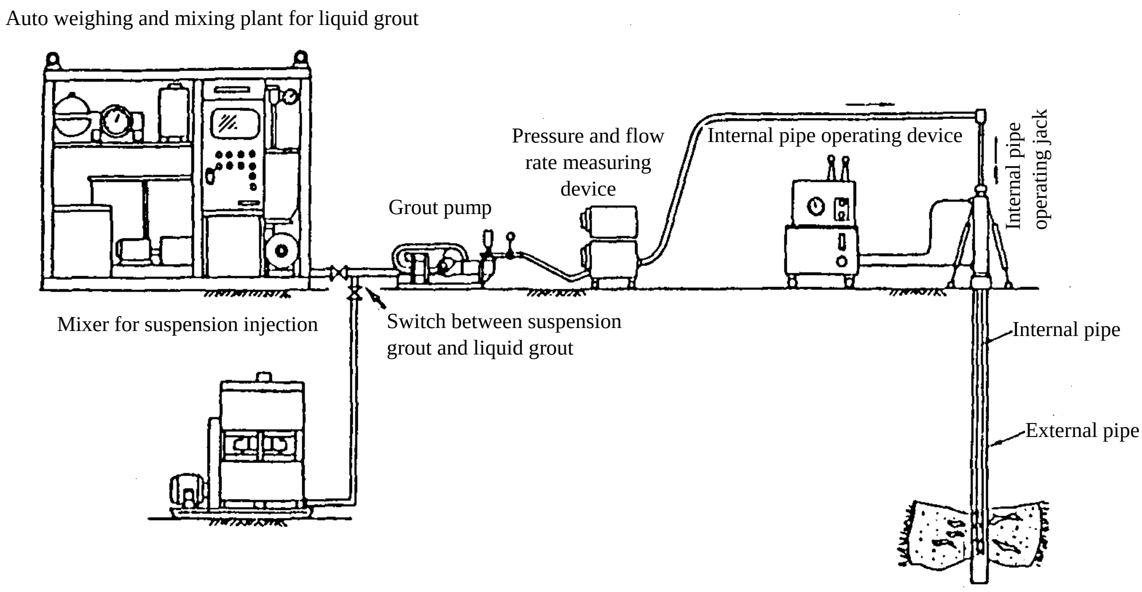
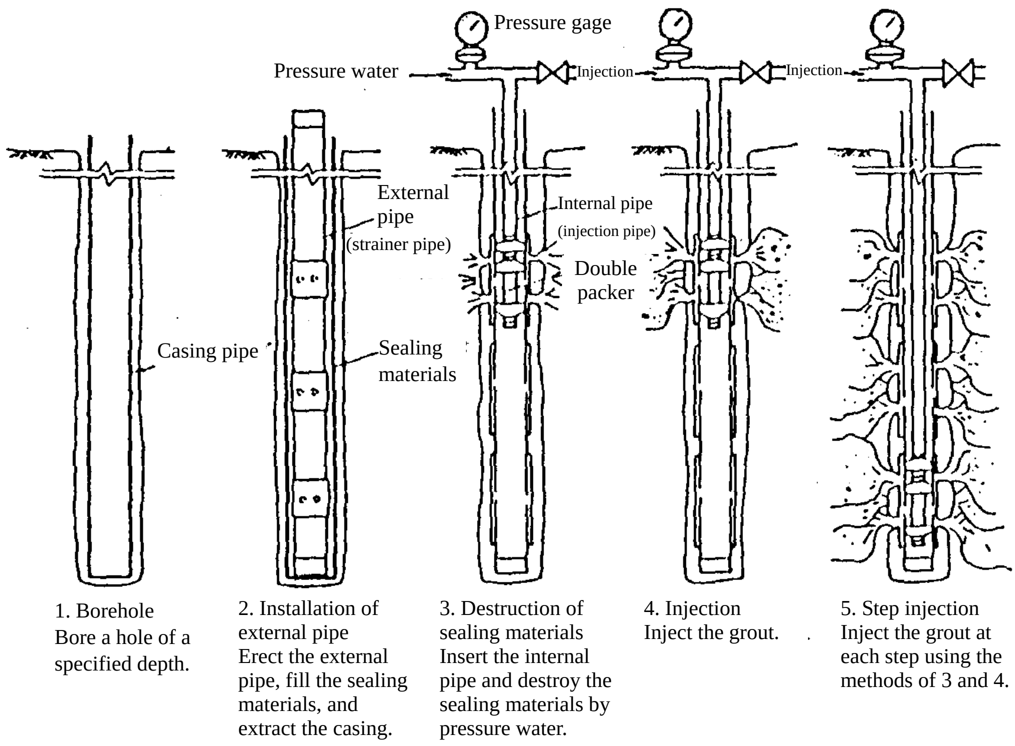


Figure 5.2.11 Construction Order of the Twin-pipe Double Packer Method

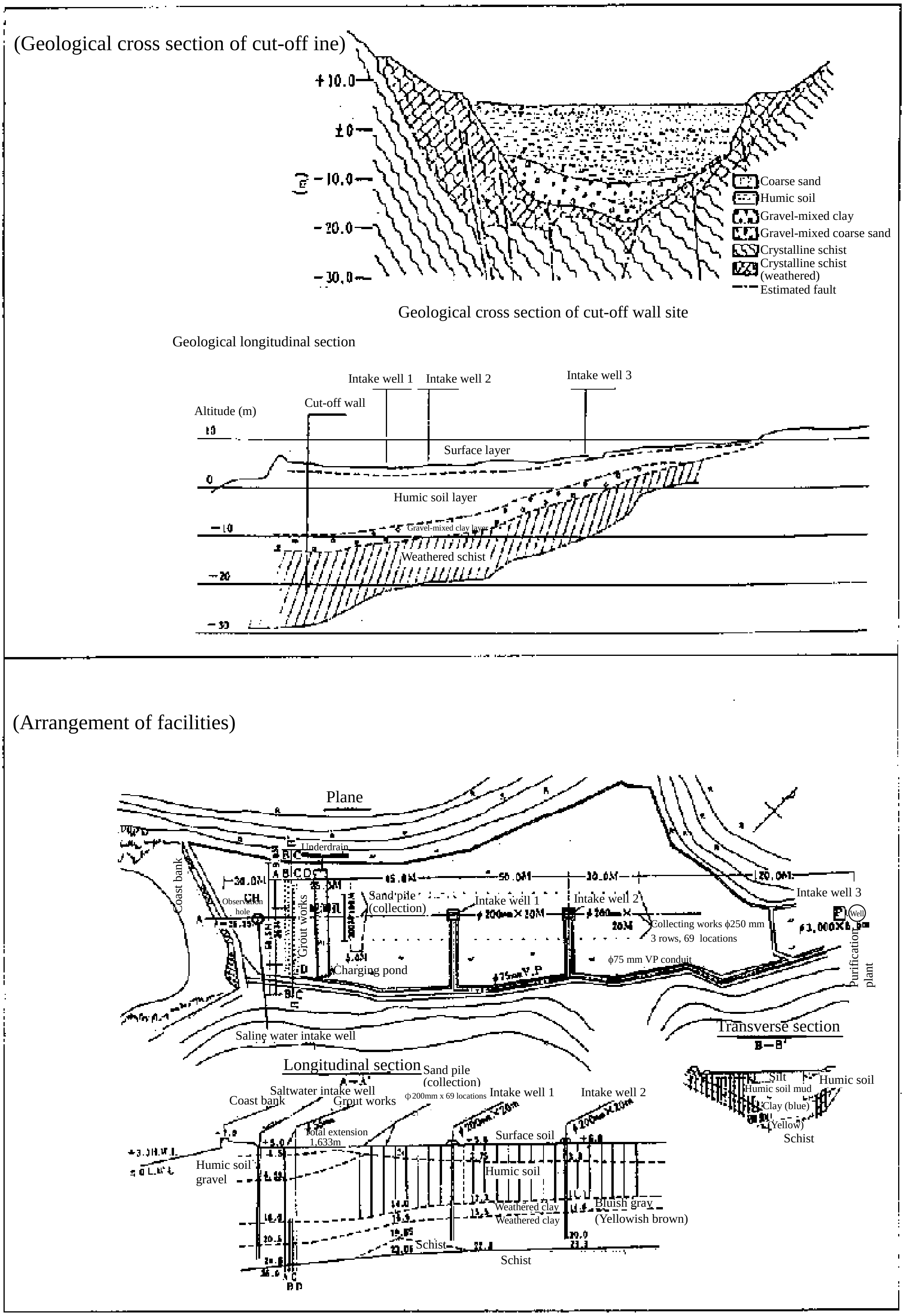


For cut-off wall construction, the twin-pipe double packer method was used at the Kabashima subsurface dam. Table 5.2.13 gives the dimensions and Figure 5.2.12 shows the sectional view of the dam axis.

Table 5.2.13 Twin-pipe Grouting Method at the Kabashima Subsurface dam

Item	Dimensions
Construction site, extension, and number of grouting holes	Site: 50 m upstream from the coast, extension: 74 m, number of holes: 75, maximum depth: 25 m
Ground	Gravel and clay layer, humic soil layer, and strongly weathered bedrock
Arrangement	Hole interval: 2 m, row interval: 2 m, two-row staggered arrangement
Grout	Cement and bentonite (10:1)
Grouting rate and pressure	300 – 600 litters/m, 0.8 – 2.9 MN/m^2
Goal of improvement	Hydraulic conductivity: 5×10^{-5} cm/sec or less
Grouting status	Since the bedrock did not accept grouting by the twin-pipe double packer method, the simple pipe rod method was adopted. The bedrock partially showed hydraulic conductivity of 10^{-4} cm/sec at the boundary of the grouting area. However, the overall imperviousness of the cut-off wall almost satisfied the goal, proving the effect of blocking saltwater infiltration.

Figure 5.2.12 Sectional View of the Kabashima Subsurface dam



(4) Jet grout method

The jet grout method is a type of grouting method that destroys the ground structure by jetting cement or other hardening materials, air, or water from inside boreholes by ultra high pressure to mix or replace the soil with hardening materials. For cut-off wall construction, the jet grout method is used at the Longhe subsurface dam in Liaoning Province and the Longkou subsurface dam in Shangdong Province in China. Table 5.2.14 gives an outline of the jet grout method used for subsurface dam construction in China. Figure 5.2.13 shows processes of the jet grout method.

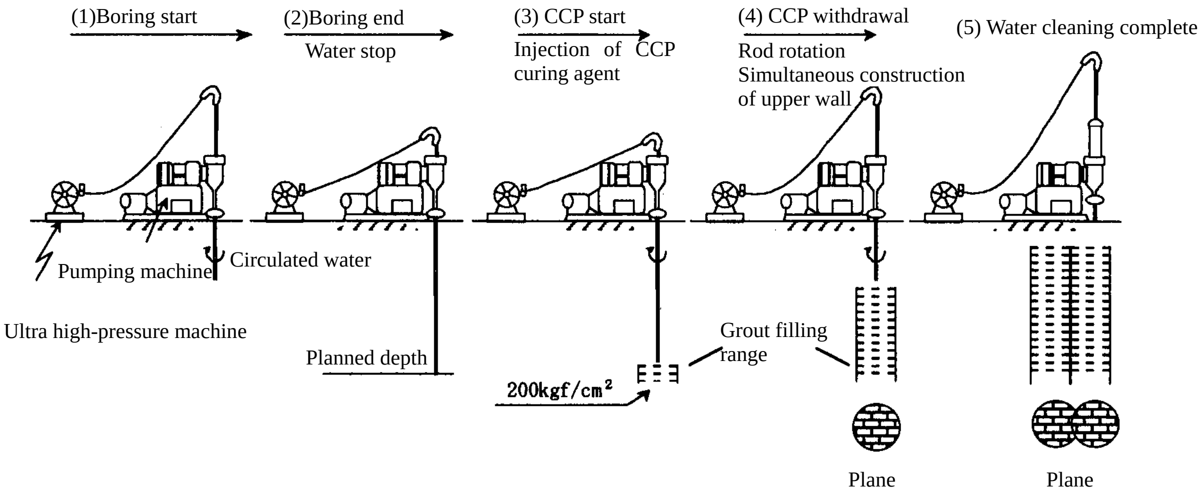
At the Longhe subsurface dam, cement milk is jetted from boreholes of staggered arrangement excavated at 1.4-m intervals along the dam axis by pressure from 30 to 40 MPa. This will construct a cut-off wall 0.4 m wide with hydraulic conductivity of 10^{-7} cm/sec.

The next mixing method is effective for an unconsolidated layer not containing gravels but not appropriate for a gravel layer. A gravel layer is generally difficult to improve only by this method but the chemical grouting method or other method is used in combination.

Table 5.2.14 Outline of the Jet Grout Method Used for Subsurface dam Constructions in China

Method	1. A grouting hole 150 mm in diameter is bored every 1.4 m for staggered arrangement. 2. The grouting nozzle is slowly lifted from the bottom of the grouting hole. While the nozzle is rotated 34° toward the adjacent grouting hole, cement milk is jetted by pressure from 30 to 40 MPa. 3. Sector walls are erected continuously to construct a cut-off wall.
Features	・ A cut-off wall 0.4 m wide in average can be constructed for hydraulic conductivity of 10^{-7} cm/sec. ・ Triple-tube casing is used for grouting and can jet high-pressure air, water, and cement milk. ・ This method cuts a stratum by high-pressure water and is applicable even to rocks. ・ Where a hole wall easily collapses, the work is done top down or excavation and grouting are repeated.
Actual use	・ Used for construction up to 50 m deep. ・ Often used to cut off water at mines.
Disadvantages	・ A wall near a grouting hole becomes thin. ・ The wall strength is small. ・ Special measures are necessary where the ground is composed of many gravels.

Figure 5.2.13 Processes of the Jet Grout Method



Concept of CCP Method

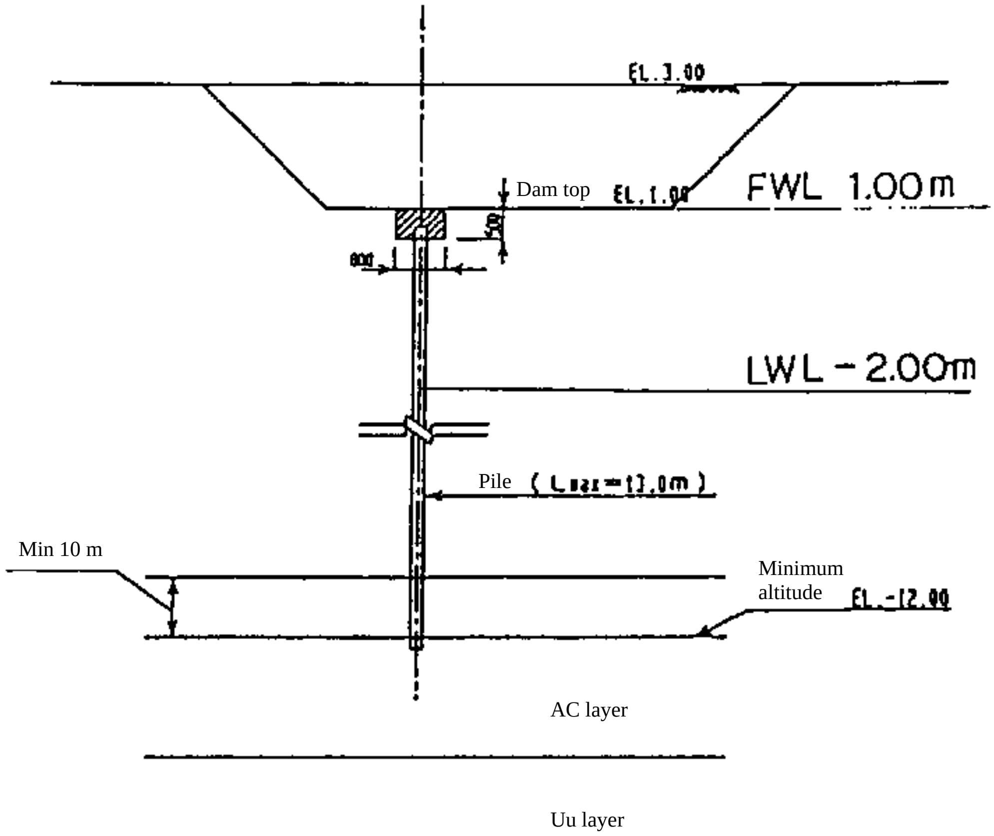
(5) Steel sheet pile method

The steel sheet pile method is to construct a cut-off wall by driving steel sheet piles continuously into the ground with a vibratory hammer. When cutting a shallow unconsolidated layer, this method can easily secure imperviousness at low costs. The cut-off walls are steel sheet piles and concrete sheet piles. There may be no need to worry about corrosion of concrete sheet piles but there are problems with end depth adjustments and the cost is higher than with steel ones.

For the Senbaru subsurface dam, the steel sheet pile method is planned. The Senbaru subsurface dam is planned in a subsurface valley along a coast. On the basement made of Meoszoic arenite and other, Quaternary diluvium and alluvium are distributed as the aquifer. There is a clay layer distributed between the diluvium and alluvium. Groundwater in the diluvium is very saline. In addition, pumping the groundwater from the diluvium may cause ground subsidence by consolidation of the clay layer. Therefore, only the alluvium was planned as a reservoir layer for the subsurface dam. To prevent infiltration of the saltwater, the alluvium will be cut off by inserting steel sheet piles 400 mm wide down to the clay layer between the diluvium and alluvium. The dam height is up to 13 m. The steel sheet piles may become corroded by the saltwater but will last for 100 years even when they are corroded up to about 5 mm deep. For construction, the ground is excavated about 2 m deep and steel sheet piles are inserted from there.

At the Senbaru subsurface dam, the downstream subsurface dam reservoir area (active capacity: 240,000 m^3) will be partially excavated and a surface reservoir (active capacity: 440,000 m^3) will be installed to store surface water for use with groundwater. Figure 5.2.14 shows a sectional view of the cut-off wall at the Chihara subsurface dam

Figure 5.2.14 Sectional View of the Cut-off Wall at the Senbaru Subsurface dam



(6) Bucket diaphragm wall method

The bucket diaphragm wall method is to excavate a subsurface groove with a clamshell-type bucket and place cement-type hardening materials for constructing a subsurface diaphragm wall.

Bucket excavators can be classified into the bar type that lowers and lifts a bucket vertically along a guide and the suspended type from which a bucket hangs. The maximum depth of excavation by the bar type is about 40 to 50 m. Soletanche KS3000, one of the suspended bucket excavators, can excavate about 50 to 60 m deep. Bucket excavators are mainly used for unconsolidated sediments. For rock excavation, rock excavators can usually be used only for soft rocks whose unconfined compression strength is 5 to 6 MN/m^2. If a rock in unconsolidated sediments makes bucket excavation difficult, an iron bit will be dropped to crack the rock.

The bucket method creates a cut-off wall from cement-type hardening materials made of cement, bentonite, gravels, and other additives. Their mixing ratio determines the strength, permeability, and wall materials pricing. The hydraulic conductivity of the wall can be reduced to the 10^{-6} cm/sec order or less. The hardening materials are used by the following two methods:

1. Wall-stabilizing slurry mixed with hardening materials (self-hardening slurry) is used at excavation and left solidified after excavation to construct the wall.
2. Usual mud water is used as slurry at excavation and replaced with self-hardening slurry after excavation by using tremie pipe or other.

(7) Cast-in-place deep mixing method

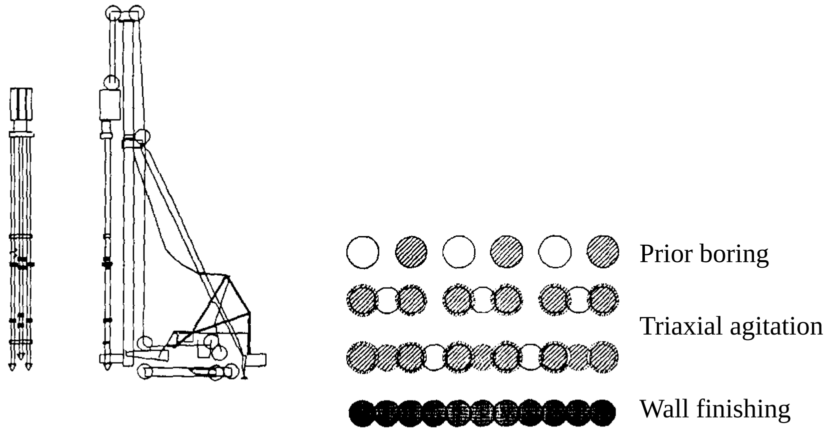
The diaphragm wall method can be used to construct a cut-off wall of permeability for secure imperviousness. A type of this method has been used for construction comparatively deep under the ground. However, this method requires a construction machine of comparatively great scale and often costs higher than the grouting method.

Of the several types of diaphragm wall method used for subsurface dam construction, the cast-in-place deep mixing method (the deep mixing method) is the most popular. The deep mixing method is to crush the ground into pillars from the surface by one or more augers and create soil cement pillars by injecting and stirring a cement suspension (liquid grout) from the tips of the augers when lifting the augers. A cut-off wall is created from continuous pillars of soil cement. This method has the following characteristics:

1. Not much soil is left after excavation because the wall is constructed by kneading soil cement on the excavation site.
2. Since soil is not completely eliminated after excavation, there is no need to stabilize the hole wall with slurry.
3. The method is applicable to a gravel layer of 50 or greater N-value and from hard to soft ground.
4. The method shows high efficiency about 15 to 20 m deep under the ground but also allows work at a depth beyond 60 m.
5. Noises and vibrations are comparatively small.
6. If there is soil containing organic clay or salt in the mixing area, the strength of soil cement is affected by the factors.

Figure 5.2.16 shows the construction machine and the arrangement of excavation holes for the deep mixing method with triaxial auger that was adopted for cut-off wall construction at the Sunagawa subsurface dam and others.

Figure 5.2.16 Construction Machine and Excavation Holes for the Cast-in-Place Deep Mixing Method



The deep mixing method may produce a bent hole as the depth increases and make the wall non-continuous. To prevent this problem, a hole is measured with an inclinometer. If measurement results indicate that the hole is bent, the curve is corrected to secure a continuous cut-off wall.

Since the deep mixing method produces soil cement from the soil excavated on the site with a liquid grout, the mixing ratio greatly affects the permeability and strength. Therefore, various boundary conditions are prepared by changing the mixing ratio and the permeability and strength are verified to determine the optimum mixing ratio.

Table 5.2.15 explains the liquid grouts used at the Sunagawa subsurface dam. When the material mixing ratio of the liquid grout is changed, the solidified strength, permeability, water dispersion prevention effect, and viscosity (torque load on auger) also change accordingly. Therefore, the mixing ratio is determined by considering the field conditions, work efficiency, and economy.

Even the optimum mixing ratio of limestone with a liquid grout depends on the field conditions. As Table 5.2.16 shows, the liquid grout used for the prior boring at the Komesu subsurface dam has a high concentration unlike that used at the Sunagawa subsurface dam because the liquid grout loses almost no water to the surrounding ground and does not increase the construction torque.

Table 5.2.15 Liquid Grouts Used for the Deep Mixing Method

Boring Process		Liquid Grout	Mixed Materials	Purpose of Injection
Prior boring	Penetration	Grout I	Adjustment slag Fly ash Bentonite	Cooling the bit of the auger Reducing the friction resistance (torque) Forming the hole wall with mud and preventing water dispersion Reserving the total quantity of hardening materials
	Pulling			
Triaxial boring	Penetration	Grout I'		
	Pulling	Grout II	Ordinary cement Bentonite Thickener, Blowing agent	Solidifying the wall and improving the strength with the residual hardening materials from Grout I

Table 5.2.16 Mixtures of Liquid Grouts for the Deep Mixing Method (Per 1.0-m Borehole)

Materials	Unit	Sunagawa Subsurface dam (1990 – 1992)			Komesu Subsurface dam (1995 – 1997)			
		Grout I	Grout I'	Grout II	Grout I		Grout I'	Grout II
		Penetration/ pulling	Penetration	Pulling	Penetration	Pulling	Penetration	Pulling
Adjustment slag (S)	kg	40.0	115.7		25.8	5.2	115.4	
Fly ash (F)	kg	12.9	21.4		8.3	1.7	21.3	
Bentonite (B)	kg	4.6	8.1	3.8	4.1	0.8	8.0	3.8
Water (W)	l	264.3	683.9	125.4	135.8	27.2	478.8	125.4
Ordinary cement (C)	kg			115.6				115.6
Blowing agent(A)	kg			9.7				9.7
Thickener (SK)	kg			0.38				0.38
Injection volume per m	l/m	286	737	167	150	30	532	167
W/SF	%	500	500		400	400	350	
B/W	%	1.7	1.2	3.0	3.0	3.0	1.7	3.0
W/C	%			100				100
SK/W	%			0.3				0.3
A/C	%			8.4				8.4

If the ground to be excavated by the deep mixing method is composed of various geological conditions, the optimum mixing ratios of liquid grouts used for excavation and solidification should be studied with extreme care.

The Nakajima subsurface dam adopting the deep mixing method for cut-off wall construction is an experimental subsurface dam constructed by the Ministry of Agriculture, Forestry, and Fisheries for technological development to realize a subsurface dam of saltwater infiltration prevention with a gravel layer as a reservoir layer. The basement of the Nakajima subsurface dam is composed of andesite, granite, and rhyolite and a drowned valley is developed on this basement. In this valley, an alluvium layer composed of clay, silt, sand, and gravels is accumulated up to 25 m thick as an aquifer. Thus, the geology on the construction site varies in strength from a soft layer with an N-value of 50 or less to soft rocks.

Regarding the design dimensions of the cut-off wall for the Nakajima subsurface dam, the width was set to 0.5 m and the hydraulic conductivity was set to 1×10^{-6} cm/sec or less. The unconfined compression strength was set to 5 kg/cm^2 at the age of 20 days for self-standing even in the soft alluvium.

At the Nakajima subsurface dam, a soil cement wall is constructed in the alluvium layer composed of a sand layer, a volcanic ash layer, a clayey sand layer, and a gravel-mixed sand layer. The permeability of soil cement is dominated by the ratio of the sand content in the excavated soil. As the sand content increases, the permeability grows. With boring samples from the sand layer, five kinds of boundary conditions were created by changing the water cement ratio and the bentonite ratio of the liquid grout. Then, an unconfined compression strength test and a permeability test were performed. According to the results, the mixing of the liquid ground was determined as shown in Table 5.2.17 to satisfy the design hydraulic conductivity (1×10^{-6} cm/s) and unconfined compression strength (5 kgf/cm^2).

Table 5.2.17 Mixture of Liquid Grouts at the Nakajima Subsurface dam (Per 1.0 m^3 of Soil)

Water to Cement Ratio W/C (%)	Bentonite to Water Ratio B/W (%)	Grouting Volume Q (%)	Blast Furnace Cement BC (kg)	Bentonite B (kg)	Water W (liter)
175	6	742	350	37	613

At the Nakajima subsurface dam, grouting pipes are erected at 90-cm intervals before the soil cement walls become solid in order to monitor saltwater infiltration through weathered rocks of the basement and inject the grout into the basement rocks for stopping water.

(8) Other methods

The large-diameter pile method, the horizontal multi-axis excavation method, and the H-type steel pile method are also being used experimentally as cut-off wall construction methods for the subsurface dam. All of these methods have produced cut-off walls of adequate imperviousness. Figures 5.2.17 to 5.2.19 shows the construction machines and the arrangement of excavation holes.

Figure 5.2.17 Large-diameter Pile Method

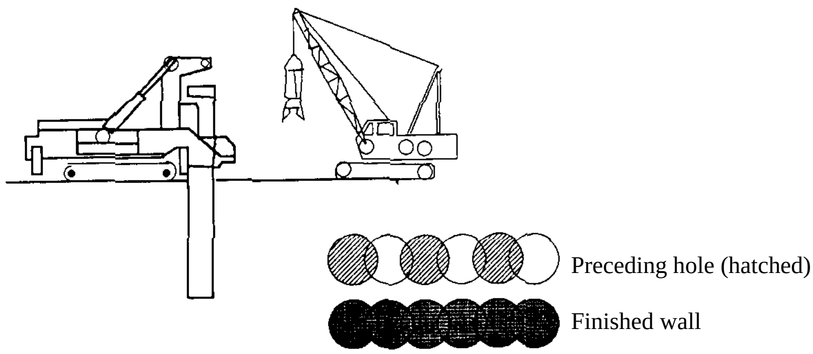


Figure 5.2.18 Horizontal Multi-axis Excavation Method

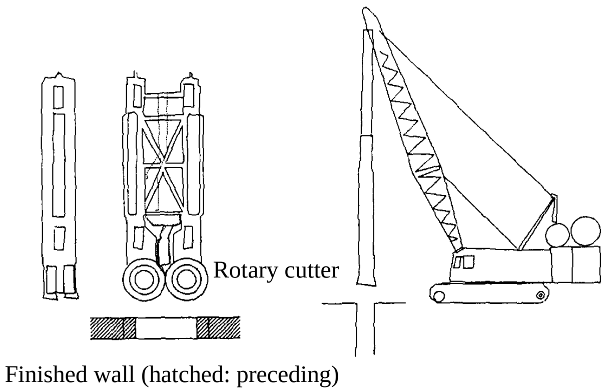
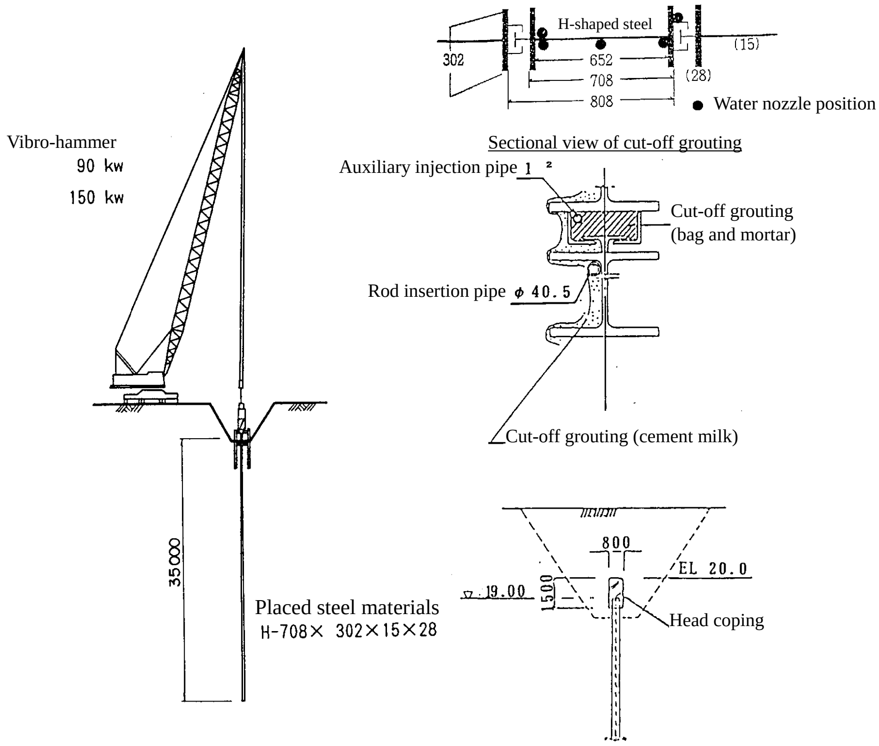


Figure 5.2.19 H-type Steel Pile Method



5.2.7 Design of subsurface dam with surface reservoir

A subsurface dam with surface reservoir is either of two types. One has a cut-off wall underground but stores surface water in a low-altitude reservoir area (Kanjin subsurface dam). The other has a subsurface dam cut-off wall directly under the surface weir to store both surface water and groundwater. Table 5.2.17 shows subsurface dams in China, with a cut-off wall whose surface weir is an open-close gate. The gate is normally closed to retain surface water but opened in the case of a flood to allow surface water to flow downstream. These surface reservoir facilities are also expected to have the effects of groundwater charging.

Table 5.2.18 Subsurface dams with Surface Reservoir in China

Dam	Surface Water Reservoir Facilities
Long he subsurface dam in Liaoning Province (Under construction)	Rubber dam
San jian bu subsurface dam in Liaoning Province (Planned)	Hydraulic auto flap gate × 4
Long kou subsurface dam in Shangdong Province (Completed)	Hydraulic auto flap gate × 4

5.3 Intake Facilities

5.3.1 Basic policy of intake design

(1) Appropriate intake facilities

When designing intake facilities for a subsurface dam, the type, structure, and arrangement should be determined for the intake of a necessary amount of water from the reservoir area even in the case of minimum reservoir level.

A subsurface dam stores water in a subsurface reservoir layer. However, the intake properties are often not uniform even in the reservoir area where the permeability of the reservoir layer changes vertically and horizontally. In addition, the basement of the reservoir area may have a very irregular surface. If intake facilities are installed where an adequate water depth cannot be secured because of intake or the permeability is low, intake may become inefficient and uneconomical. When installing intake facilities, therefore, it is necessary to select an appropriate place by survey and analysis of the intake properties of aquifers and to determine the type and structure of intake facilities conforming to the intake properties.

Since a subsurface dam generally requires power to pump groundwater, the operating and maintenance costs of the intake facilities should also be fully considered.

(2) Types of intake facilities

When selecting the type of intake facilities, the necessary amount of intake and the construction and operational costs must be discussed in detail as well as the topographical, geological, and groundwater conditions to select facilities conforming to the hydraulic characteristics of the aquifer and the form of water use. Intake facilities can be classified by type of collection into the decentralized intake type and the centralized intake type.
For decentralized intake, many facilities of a comparatively small scale per place are installed. Ordinary tubular wells are used. Intake facilities of the decentralized intake type allow the position and quantity of installation to be adjusted according to the past amounts of intake and the intake properties of the aquifer. Because of the many facilities, however, this type is difficult to maintain.

For centralized intake, a small number of large facilities are installed. Collecting wells and adits correspond to these facilities. Intake facilities of the centralized intake type are easy to maintain but carry high installation costs because of the large scale. Therefore, the intake properties on the scheduled site must be surveyed well in advance to achieve the required function. In general, this type is not suitable where the groundwater level is high because working below the groundwater surface is difficult. When creating an adit or a horizontal hole for a collecting well, the hole wall under construction must be stable.

For a subsurface dam with surface reservoir, the intake and drainage facilities may have the same structures as those of an ordinary surface dam depending on the shape of the ground reservoir. If the reservoir surface is in the ground reservoir at the minimum reservoir level, the intake facilities may have only the surface water intake function. However, the intake plan and the position and structure of intake facilities should be determined by considering that it takes a long time for groundwater to flow out from the reservoir layer to the surface reservoir.

Table 5.3.1 compares the intake facilities used for subsurface dams.

(3) Arrangement of intake facilities

Intake facilities are expected to allow a planned amount of water to be taken in even when the reservoir level is low. Therefore, intake facilities shall basically be installed in a reservoir area where adequate water is available for the maximum intake and the necessary intake at the minimum reservoir level. Usually, a suitable place for intake facilities is where the depth to the top surface of the basement is deep and the aquifer is thick. By considering mutual interferences between intake facilities, select a place where an adequate amount of water is available. If the permeability and other intake properties of a reservoir layer are not uniform, it is necessary to select a place not only conforming to the above conditions but also having high permeability and allowing the immediate intake of reservoir water.

Table 5.3.1 Comparison of Intake Methods

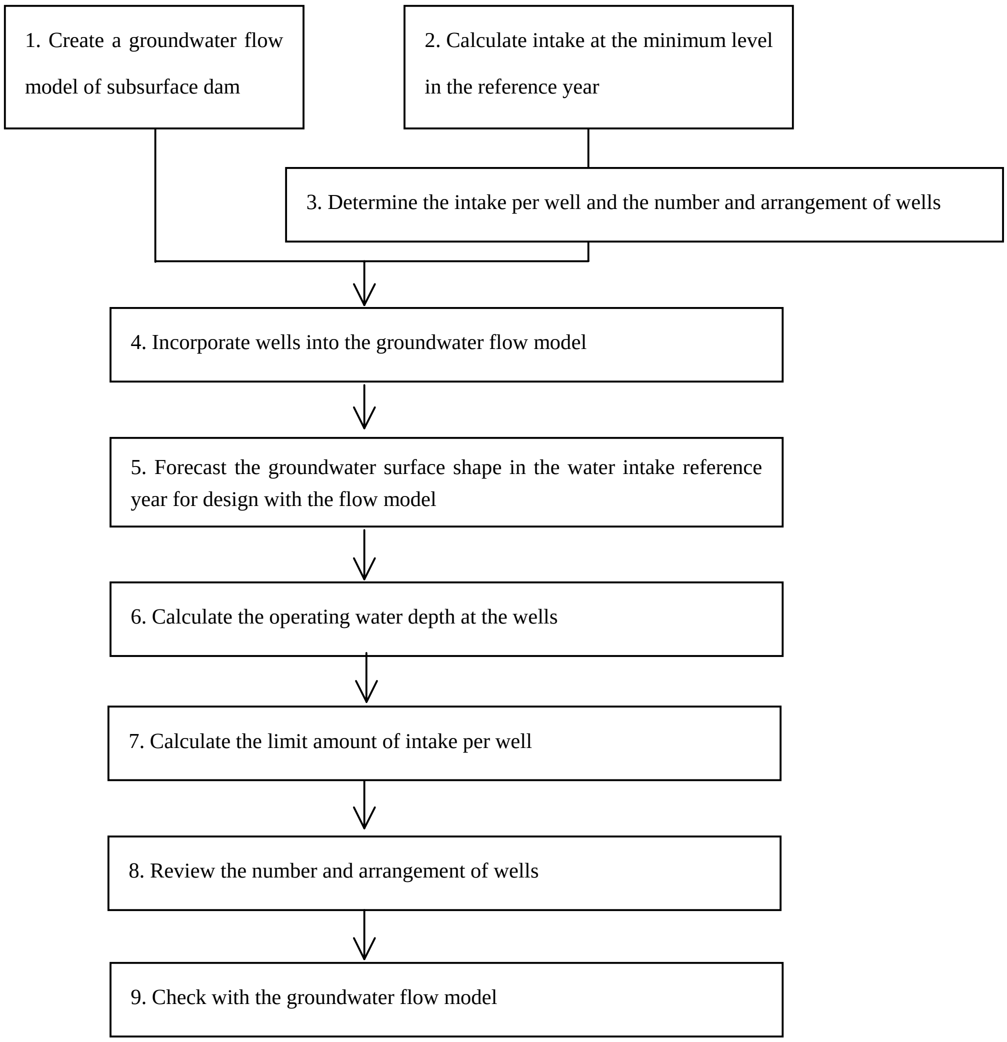
Type	Tubular well	Collecting well	Vertical hole and collecting horizontal hole	Underdrain (collecting trench)
Intake	This is for spot intake. The intake per point is smaller than that from a collecting well or a collecting horizontal hole. For large intake per spot, the well should be constructed where the basement surface is deep and an adequate water level can be secured in the well.	This is for plane intake. Since intake does not create remarkable irregularity in the groundwater surface, this method is excellent for the effective use of reservoir water.	Local changes of aquifer properties near a horizontal hole may lower the intake efficiency.	This is suitable for a subsurface dam of a low water level. For greater intake, extension is necessary.
Construction	Machine excavation is available, irrespective of the groundwater level at construction. For manual excavation, a low groundwater level is preferable. This type of construction from the surface is easy and exhibits no safety problems. The construction costs are comparatively low. Extension is easy.	A low groundwater level at construction is preferable. If work below the groundwater surface becomes necessary, this method becomes costly because temporary facilities to lower the groundwater level and underwater work become necessary. To avoid subsurface work, it is preferable to complete the work before the dam increases the reservoir level. If a horizontal hole is greatly extended, hole bending may occur. If the yield becomes insufficient, more horizontal holes should be added.	Same as "Collecting well" If a horizontal hole is created under water pressure, safe excavation work should be considered because a freshet is anticipated. If the horizontal hole function becomes low, new horizontal holes should be added. However, this work is costly because it is done under water. At the excavation of a horizontal hole, the hole wall should be stable.	A low groundwater level at construction is preferable. An underdrain is constructed mainly by the open-cut method. As the depth increases, the level of work efficiency lowers.
Intake management	If the number of wells increases, management becomes complicated.	Since the intake per well is large, the number of facilities decreases and intake management becomes easy.	Same as "Collecting well"	
Maintenance	Blinding around the screen can be solved by surging or chemical treatment. If the number of wells increases, pump management becomes complicated and pump updating poses a problem.	If a horizontal well becomes lower than the groundwater level, it may be difficult to solve the problem of blinding. If the horizontal hole function becomes low, new horizontal holes should be added. However, this work is costly because it is done under water.	Solving the blinding of a horizontal hole may be difficult because it may require underwater work.	If an underdrain is blinded, a hose is inserted and the underdrain is washed using high-pressure water jetting. The function of impervious materials is difficult to recover.
Case and reason for adoption	Sunagawa subsurface dam The groundwater level is high and a collecting well cannot be constructed. The reservoir imperviousness is obviously not even. A difference of intake efficiency is anticipated and it is difficult to locate a collecting well. The past intake per tubular well was up to 2,000 m^3/day.	Kikai subsurface dam Facilities can be constructed in a wide range. The intake per well is high. If the groundwater level is found to be high before dam construction, collecting wells can be constructed.	Minafuku dam These facilities were constructed experimentally for a large-scale intake test.	Senbaru subsurface dam The groundwater level is low. Judging from the test results, intake using an intake trench is possible and no horizontal hole or other is necessary. Economical digging is possible.

5.3.2 Analysis of intake

(1) Design of tubular well

When designing tubular wells, the amount of intake per tubular well and the necessary number and arrangement of tubular wells should be determined to ensure the maximum intake and the necessary intake at the minimum reservoir level in the water intake reference year for design according to the subsurface dam operation plan (water supply plan). Figure 5.3.1 shows a case of designing tubular wells for intake at the minimum reservoir level in the water intake reference year for design. The maximum intake should also be studied in the same way.

Figure 5.3.1 Case of Tubular Well Design Flow



1. Constructing a groundwater flow model of the subsurface dam

Create a groundwater flow model to forecast the shape of the groundwater surface in the reservoir area at intake in detail. The preferred model divides the reservoir area into small segments using the finite element method or the finite difference method.

2. Calculating the intake at the minimum reservoir level in the water intake reference year for design

Calculate the necessary intake at the minimum reservoir level in the water intake reference year for design according to the subsurface dam operation plan. The minimum reservoir level (dead water level) in the subsurface dam plan means the lowest level that the reservoir water reaches when used in the water intake reference year for design. This is calculated from groundwater charge and intake by water balance analysis.

3. Determining the tentative number and arrangement of tubular wells

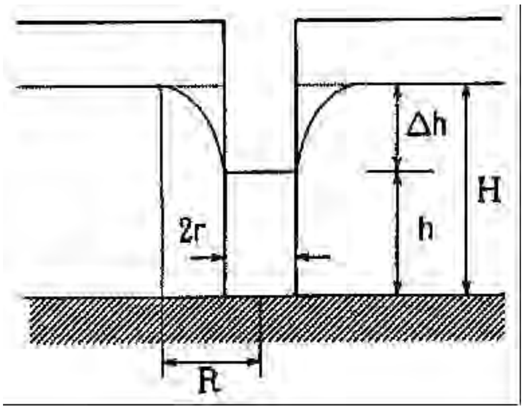
Check the hydraulic constants of the aquifer and the groundwater level. Next, calculate the maximum yield per tubular well using the equation given below. The initial depth (H) is the water depth at the minimum reservoir level of the subsurface dam obtained by the water balance analysis (see Figure 5-20).

$Q = \pi \times k \times (H^2 - h^2)/\ln(R/r)$ ・・・・・・・・・・・・・・・・・・・・・・・Eq. (1)

Q: Yield   k: Hydraulic conductivity   H: Initial water depth   h: Operating water depth

R: Radius of influence area   r: Radius of well

Figure 5.3.2 Calculating the Maximum Yield Per Tubular Well



According to the results of a pumping test, the radius of the influence area was 300 to 600 m in the Miyako district. Therefore, 400 m was adopted for the design. In addition, various formulas are proposed. One of them is the following:

$R = 3000 \times \Delta h \times (\sqrt{k})$

R: Radius of influence area (m)   Δh: Water level fall (m)   k: Hydraulic conductivity (m/sec)

Within the maximum yield, determine a planned yield per tubular well. To determine the required number of tubular wells, divide the necessary intake at the minimum reservoir level by the planned yield per tubular well.

4. Incorporating tubular wells into the groundwater flow model

Arrange the above-studied tubular wells in the reservoir area. To secure an operating water depth, select where the depth to the top surface of the basement is deep and the reservoir layer has good permeability. To prevent interferences at intake, keep an appropriate distance between tubular wells. To forecast the groundwater level at intake from installed tubular wells, incorporate the wells into the groundwater flow model.

5. Forecasting the groundwater surface shape and calculating the water depth at each tubular well
From the groundwater flow model corrected in 4, obtain the groundwater surface in the water intake reference year for design and calculate the water depth at each tubular well at the minimum reservoir level.

6. Calculating the operating water depth at the tubular wells
Considering errors and well losses by modeling, correct the water depth obtained in 5 and estimate the actual operating water depth.

7. Calculating the limit amount of intake per tubular well
From the operating water depth obtained in 6, judge whether the planned yield is available by using the following formula for the hydraulic gradient limit:

$Q = \pi \times D \times L \times (\sqrt{k})/15$

Q: Yield (m^3/s)   L: Operating section length of the well screen (Operating water depth) (m)
D: Diameter of the well (m)   k: Hydraulic conductivity (m/s)

8. Reviewing the number and arrangement of tubular wells
Check that the necessary operating water depth for the planned yield is secured at all wells and determine the necessary number and arrangement of tubular wells. If a planned yield is found to be unavailable from a tubular well in 7, return to 3 and review the planned yield per tubular well and the number and arrangement of tubular wells.

When not using the groundwater flow model, judge the appropriateness of the intake plan by calculation based on the following well group theory keeping in mind the mutual interferences of wells.

Formula of well group $$H^{2-} hi^2 = \sum_{i=1}^{n} Qi/(\pi k)\ln(R/ri) + \sum_{i=1}^{n}{}' Qi/(\pi k)\ln(rij/ri)$$

H: Initial water depth, hi: Operating water depth in the i-th well, Qi: Intake from the i-th well, R: Radius of influence area, k: Hydraulic conductivity, rij: Distance between the i-th well and the j-th well, ri: Radius of the i-th well, Σ’: Total sum of i = 1 to i = n, excluding i = j

The design of tubular walls for the Sunagawa subsurface dam is exemplified here. In general, reducing the number of tubular wells is more economical. If the intake per tubular well is increased, however, the water level fall becomes large and the necessary intake cannot be secured at a low reservoir level. The planned intake per well is determined from the hydraulic conductivity and storage coefficient of the aquifer and also the tolerance of water level fall in the well. For the Sunagawa subsurface dam, the upper limit of planned intake per tubular well was set to 2,000 m^3/day on the basis of pumping test results. Thus, the necessary number of wells was determined to be 70.

By intake simulation in the water intake reference year for design, the minimum reservoir level at the Sunagawa subsurface dam was assumed to be EL.7.1 m. When placing tubular wells in a reservoir area, it is necessary to ensure intake of 2,000 m^3/day until the groundwater decreases to the minimum reservoir level. At the Sunagawa subsurface dam, the minimum well depth for the intake of 2,000 m^3/day is calculated to be 6.6 m. Thus, the basement top altitude allowing tubular wells is 7.1 – 6.6 = EL.0.5 m or less.

If the distance between wells is reduced, intake causes mutual interferences, increases the water level, and disables necessary intake. Therefore, the inter-well distance at the Sunagawa subsurface dam was set to 50 m or greater.

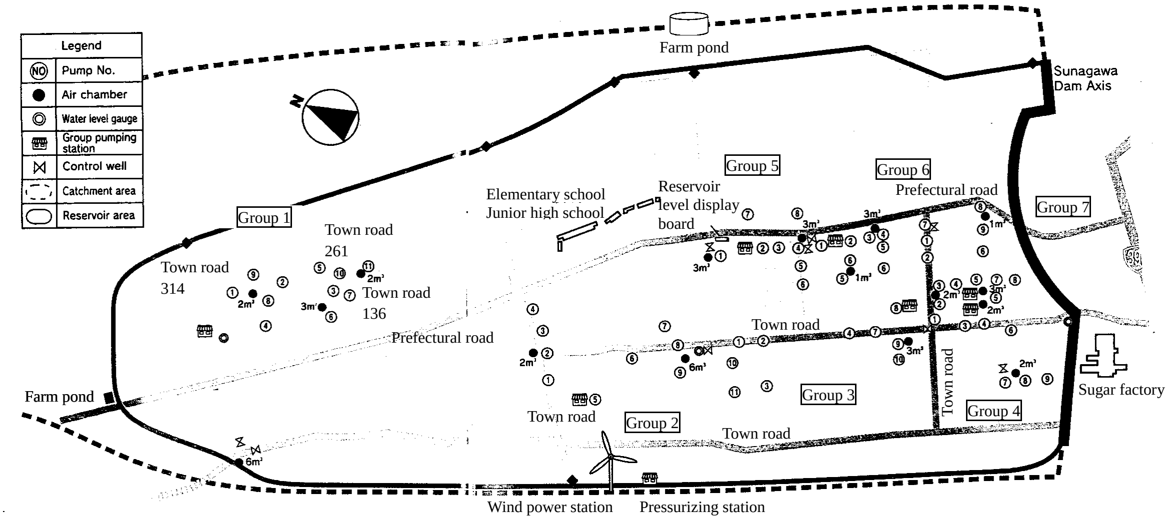
To ensure the intake capacity of a well, select a point where the aquifer permeability is great and the intake properties are good.

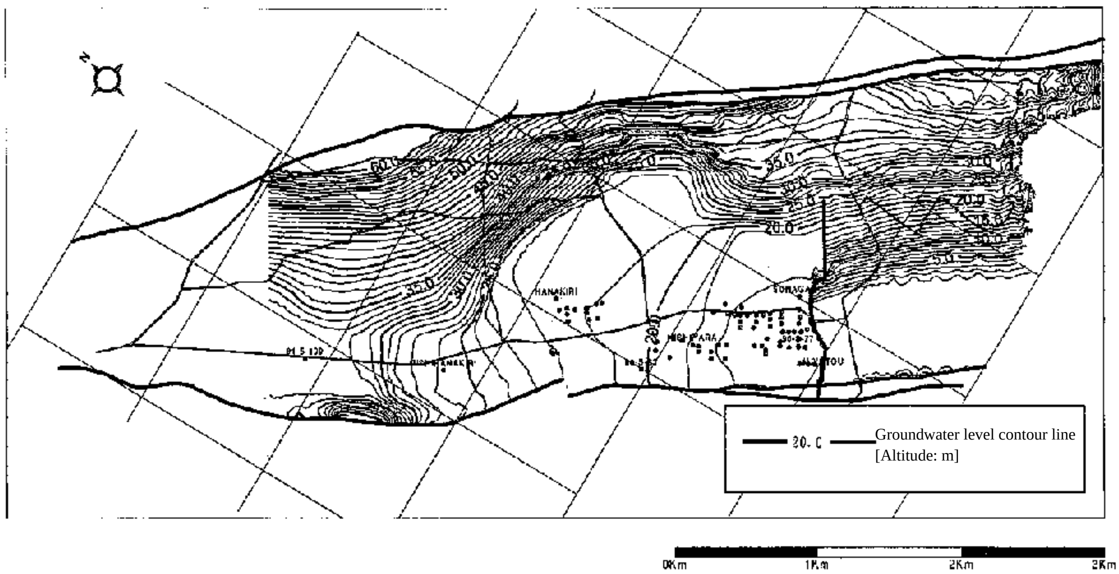
After the above discussions, the tubular well arrangement conditions at the Sunagawa subsurface dam were set to the following:

1. The basement top altitude shall be within the prescribed value (EL.0.5m).
2. The tubular well interval shall be 50 m or more.
3. The aquifer shall have good intake properties.

The aquifer at the Sunagawa subsurface dam is composed of limestone but its permeability differs greatly depending on the place. When the correlations between the properties of limestone and the permeability were surveyed with a boring core, the permeability was found to decrease as the content of inflow clay in limestone cavities increases. Therefore, the basement top altitude was checked and the distribution of inflow clay was clarified by boring survey and other. In addition, intake was simulated with a model that can reproduce groundwater flows reflecting the differences of permeability based on the distribution status of inflow clay and also hydrological and geological structures. By considering these factors, a tubular well arrangement plan (Figure 5.3.3) satisfying the conditions of 1 to 3 above was determined also to secure the necessary intake in the water intake reference year for design (1974). Prior to the arrangement of tubular wells, the intake properties were checked by a simple pumping test using boring of 100 mm in diameter.

Figure 5.3.3 Arrangement of Tubular Wells at the Sunagawa Subsurface dam





Groundwater level distribution at intake (September 25, 1974)

When designing pumps for intake, the following dimensions must be determined:

1) Intake method and number of pumps
2) Pump model
3) Pump diameter
4) Discharge per pump
5) Total head (Altitude of water supply area – Minimum altitude of intake + Pipe loss and other)
6) Motor type and output
7) Operation control method

(2) Design of collecting well

When designing collecting wells, the planned yield per collecting well and the necessary number and arrangement of collecting wells should be determined in the same way as tubular wells above to ensure the necessary intake at the minimum reservoir level in the water intake reference year for design by considering interferences between collecting wells.

A collecting well is a vertical hole with radially arranged horizontal holes for intake. When designing a collecting well, the number of horizontal holes, the installation depth, and the extension per hole must be determined. To ensure the planned intake, check “Altitude of the minimum reservoir level in the water intake reference year for design > Altitude of the horizontal hole end > Altitude of the minimum pumping water level.”

To find the yield per collecting well, set the radius of well (r) to the distance from the center of the collecting well to the end of the horizontal hole in Eq. 1 used to calculate the intake from the tubular well.

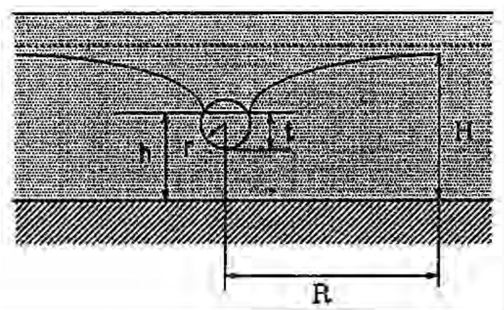
Calculate the amount of collection per horizontal hole as follows (Figure 5.3.4):

$$Q = k(H^2-h^2)L/R \times \sqrt{(t+0.5r)/h} \times \sqrt[4]{(2h-t)/h}$$

Q: Amount of collection per horizontal hole, L: Extension of horizontal hole, H: Static water level, h: Water depth in horizontal hole, R: Radius of influence area, r: Radius of horizontal hole, k: Hydraulic conductivity, t: See below

(When the h value reaches several times the diameter of horizontal hole (2r))

Figure 5.3.4 Amount of Collection by Horizontal Hole



(3) Design of collecting adit

Intake from a collecting adit can be calculated as follows (Figure 5.3.5):

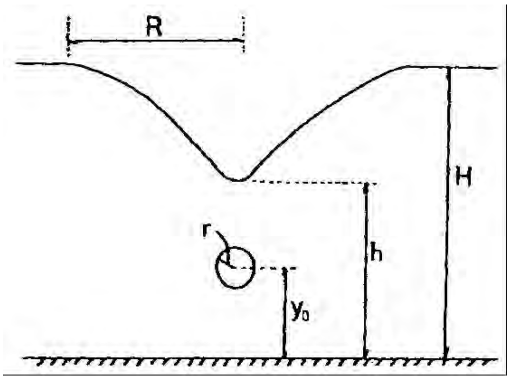
$$Q = \frac{2\pi k(H-h)\times L}{\ln\left[\{\sinh^2(\pi R/2h)+\sin^2(\pi R/2h)-1\}/\{\sin^2(\pi(y_0+r)/2h)-\sin^2(\pi y_0/2h)\}\right]}$$

Q: Amount of intake, k: Hydraulic conductivity, L: Length of adit, r: Radius of adit,

R: Radius of influence area, H: Natural water depth, h: Operating water depth,

y_0: Depth from the adit center to the basement top (low-permeability layer)

Figure 5.3.5 Intake from Collecting Adit



5.3.3 Structures of intake facilities

(1) Structure of tubular well

A tubular well consists of a casing, a screen, filler (filter) between the screen and ground, and an intake pump. When designing a tubular well, determine their dimensions.

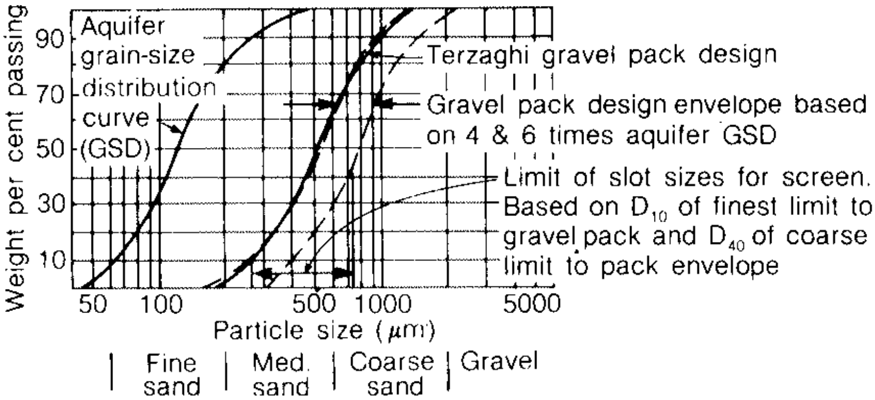
When using a submersible pump for intake, make the well diameter large enough to accept a submersible pump of the required performance and to ensure a water flow for adequate cooling. Determine the well diameter by also considering the external diameter of the pumping pipe connection flange, the size of the water level gage used for pump control, the size of the power cable, the misalignment of the center line by flange joint or other, and the margin for pump installation and repairing.

Install a casing for hole wall protection. The casing shall be made of steel pipes or other for adequate strength against buckling. To prevent corrosion, zinc-plated steel pipes are preferred.

It is preferred that the screen has an adequate aperture. For a slit or round aperture, the aperture ratio should be about 3 to 5% to ensure the required strength. Some types of screen may have an aperture ratio of about 20% by reinforcing with winding.

With the progress of pumping, sand is often sucked into the well from the aquifer around the screen. If a well is installed where the aquifer is an unconsolidated sand layer, sand around the screen may flow through the screen holes into the well at pumping or inundation around the well to bury the well and cause subsidence around the well. To prevent this kind of sucking, fill the area between the screen and the hole wall with fine gravel of an appropriate grain size as a filter. As in Figure 5.3.6, the filled fine gravel shows distribution similar to that of an aquifer. The grain size is preferred to be about four to six times the aquifer grain size. The appropriate filter thickness is 75 to 150 mm.

Figure 5.3.6 Filter Grain Size (Clark, 1988)

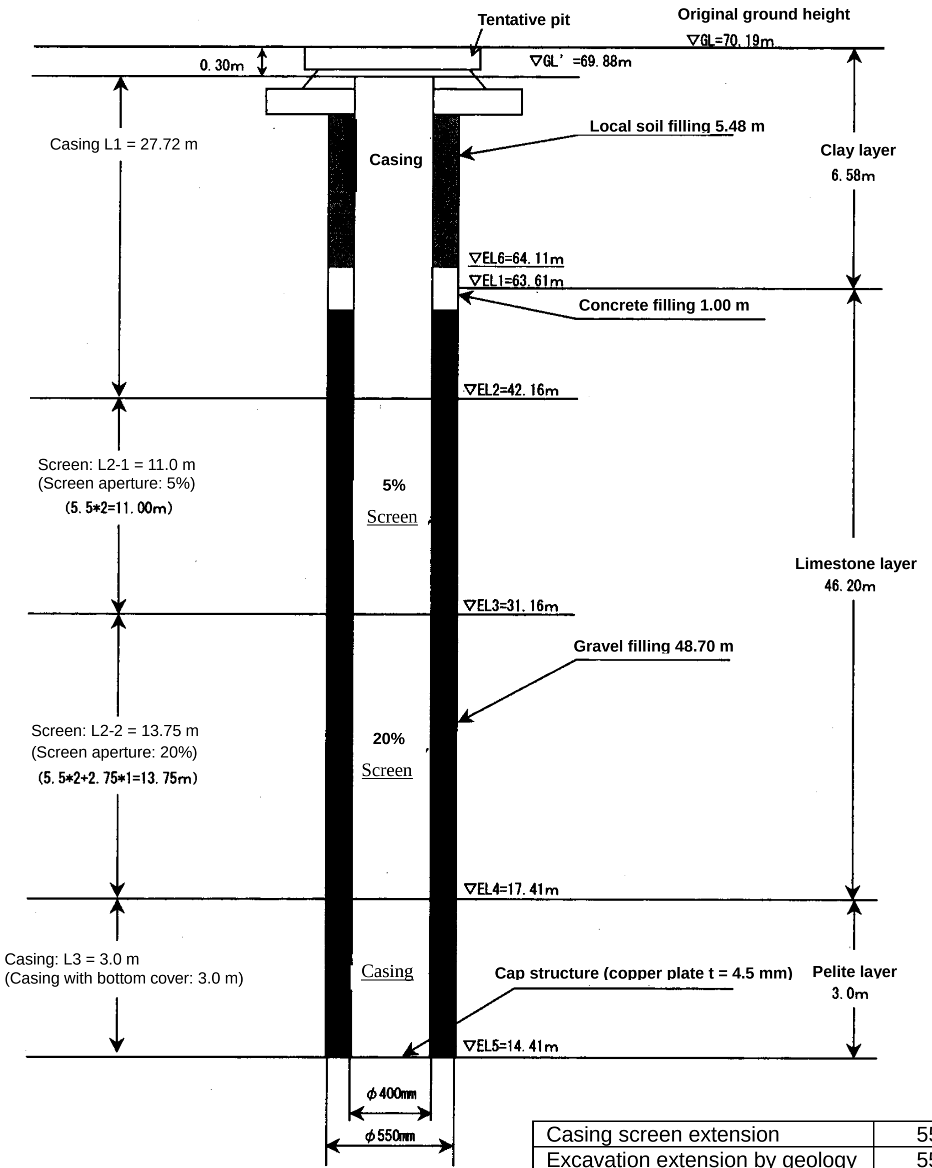


At the Sunagawa subsurface dam, holes of 550 to 600 mm in diameter were excavated and casings of 400 mm in diameter were inserted. The bottom of a hole was 3 m from the top of the basement and filtrated with sand. Between the basement and the minimum reservoir level, a winding-type screen of 20% in aperture ratio showing good intake properties was installed to ensure stable intake even at a place of shallow water. Between the minimum reservoir level and the mean reservoir level, a low-cost 5% screen created from casing by slit processing was installed. At about 1 m above the submersible pump, a water level gage was installed so that the pump would stop automatically to prevent cavitation if the water level in the well reaches that level. Table 5.3.2 exemplifies the design of the Sunagawa subsurface dam and Figure 5.3.7 shows the structure of tubular well.

Table 5.3.2 Design of Tubular Well at the Sunagawa Subsurface dam

Design item	Tubular well at the Sunagawa subsurface dam
Depth of well	–3 m from the basement top
Excavation diameter	550 to 600 mm (with rotary boring machine)
Casing diameter	400 mm
Casing material	Anti-corrosive steel pipe (carbon steel pipe for piping, plated with zinc (400 g/m^2 min))
Screen type	From the basement top to the minimum reservoir level: Winding-type screen (Aperture ratio: 20%, slit size: 1 mm) From the minimum reservoir level to the mean reservoir level: Slit screen (Aperture ratio: 5%)
Bottom structure of well	Cover (steel plate) to prevent slime suction from the bottom of the well
Sand infiltration	3 m
Filler	Aquifer : Crushed stone of single grain size (River gravel of grain size from 5 to 13 mm) Aquifer top : Concrete placement in 1-m section Aquifer top to surface : Backfilling with slime
Pump type	Submersible motor pump
Pump capacity	Diameter: 125 mm, output: 37–55 kW, discharge: 2,000 m^3/day
Pump location	Where 2 m or greater water depth can be secured between the minimum reservoir level and the top of the pump (Actually, about one meter from the basement top)

Figure 5.3.7 Structure of Tubular Well at the Sunagawa Subsurface dam



Casing screen extension	55.47 m
Excavation extension by geology	55.78 m
Backfilling or filling extension	55.18 m

(2) Structure of collecting well

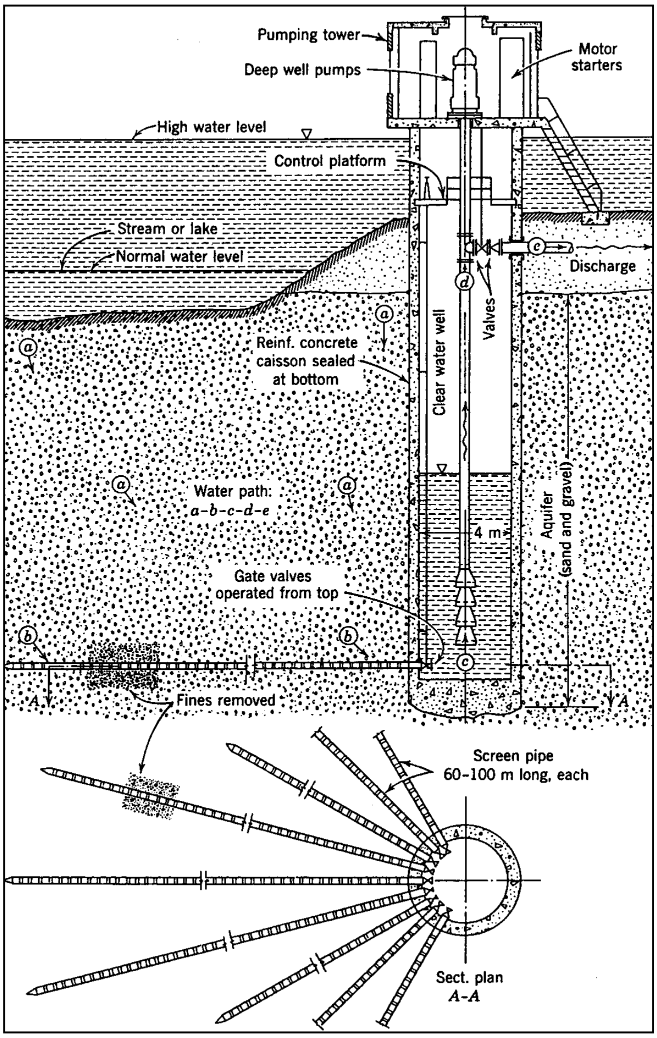
A collecting well is a vertical hole with radially arranged horizontal holes in an aquifer.

The vertical hole is excavated manually, with a bucket excavator, or by blasting. Under the groundwater surface, subsurface work becomes necessary and raises the construction costs. For cost reduction and safety, it is preferable to reduce work under the groundwater surface. To protect the hole wall during and after excavation, install casings, such as reinforced concrete frames, liner plates, and field-placed concrete. By considering the pressure from the excavated ground, casings of adequate strength must be used. Calculate the pressure on the collecting well using the formula of Terzaghi and other. The internal diameter of a vertical hole is often 3.0 to 3.5 m to reserve working space. For a vertical hole longer than 20 m, 3.5 m or greater diameter is preferable for safe work.

The number of horizontal holes per well and their extensions should be determined to secure the required amount of intake. Extending the horizontal holes allows greater intake but increases hole bending and lowers efficiency both in intake and construction. In addition, long extensions are apt to cause interferences with adjacent intake facilities. Therefore, determine the extensions of horizontal holes by considering the precision of excavation and the efficiency of intake. At the Kikai subsurface dam, the extensions of horizontal holes are limited to 50 m by considering hole bending. To retain the wall of a horizontal hole, a steel pipe with hole is inserted into the hole.

Figure 5.3.8 shows the general structure of a collecting well.

Figure 5.3.8 Structure of Collecting Well



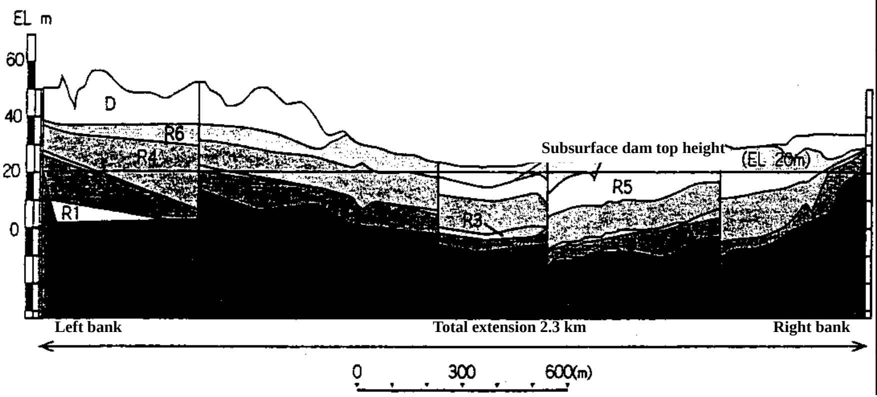
At the Kikai subsurface dam, collecting wells were adopted as intake facilities. Table 5.3.3 gives the dimensions of the collecting wells and Figure 5.3.9 shows the arrangement of wells and the well structure.

Table 5.3.3 Dimensions of Collecting Wells at the Kikai Subsurface dam

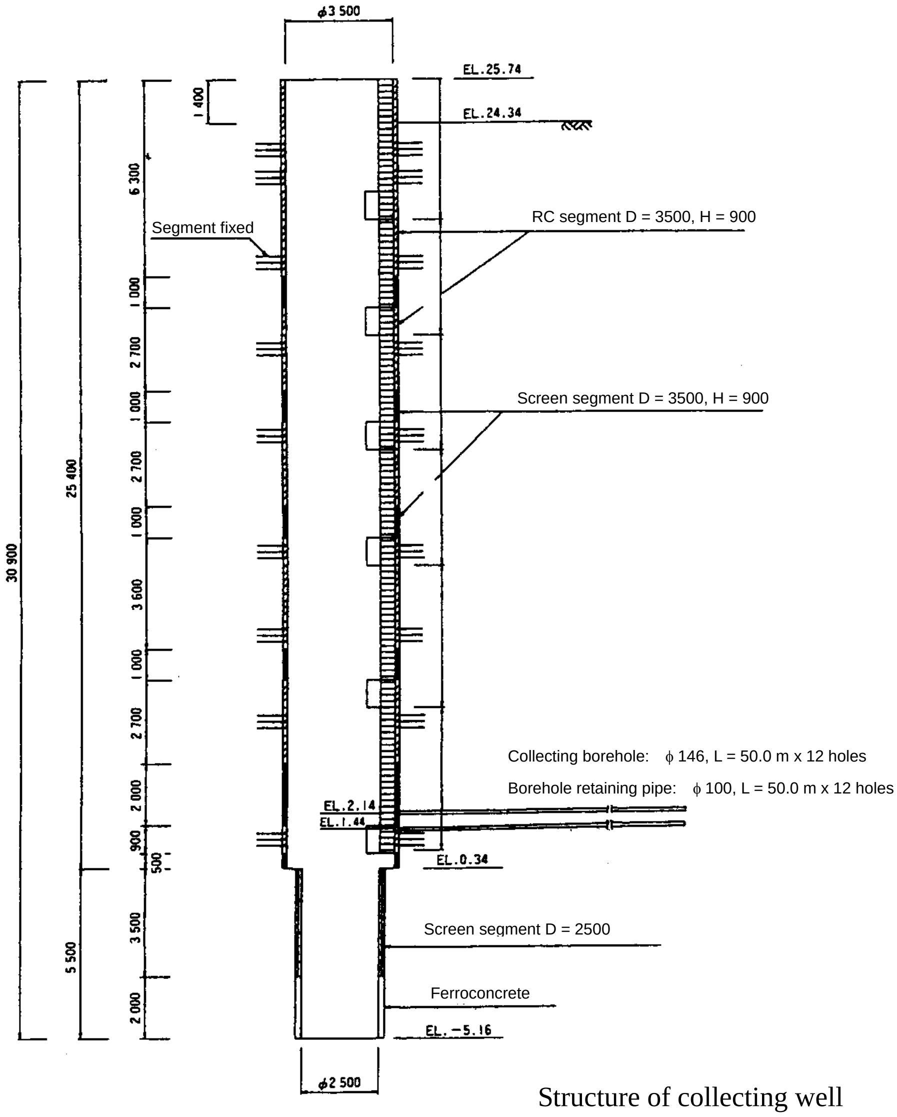
<table>
<tr><th>Item</th><th colspan="2">Specification</th></tr>
<tr><td>Quantity</td><td colspan="2">8 wells (at every 150 m in the reservoir area)</td></tr>
<tr><td>Planned intake</td><td colspan="2">Total: 46,900 m^3/day (Per well: 3,200 to 8,700m^3/day)</td></tr>
<tr><td rowspan="3">Vertical hole</td><td colspan="2">Depth: 28.80 to 37.80 m</td></tr>
<tr><td>Shallower than the groundwater surface at excavation</td><td>Diameter: 3.5 m, machine excavation (Caisson type pile method)
Reinforced concrete segment casing</td></tr>
<tr><td>Deeper than the groundwater surface at excavation</td><td>Diameter: 2.5 m, machine excavation (Boring method)
Field-placed concrete casing</td></tr>
<tr><td>Horizontal hole</td><td colspan="2">21 to 24 holes per well (2 levels × 10 to 12)
Diameter: 80 to 100 mm, extension: 50 m, end interval: about 15 m</td></tr>
</table>

Figure 5.3.9 Arrangement of Wells at the Kikai Subsurface dam and the Well Structure

Plane view of the dam



Legend		
Geological category		Symbol
Dune sand		
Sand limestone	Foraminifera sand layer	R6
	Foraminifera limestone	R5
Clastic limestone		R4
Large foraminifera limestone		R3
Calcaleous algae limestone		R2
Base gravel layer		R1
Pelite		Si

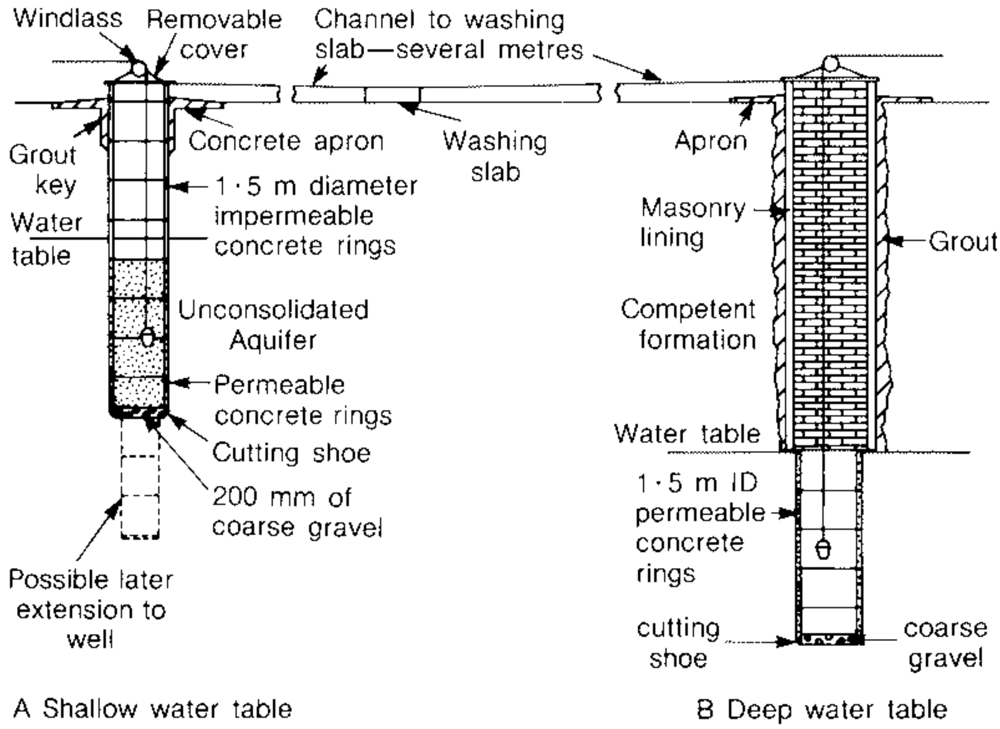


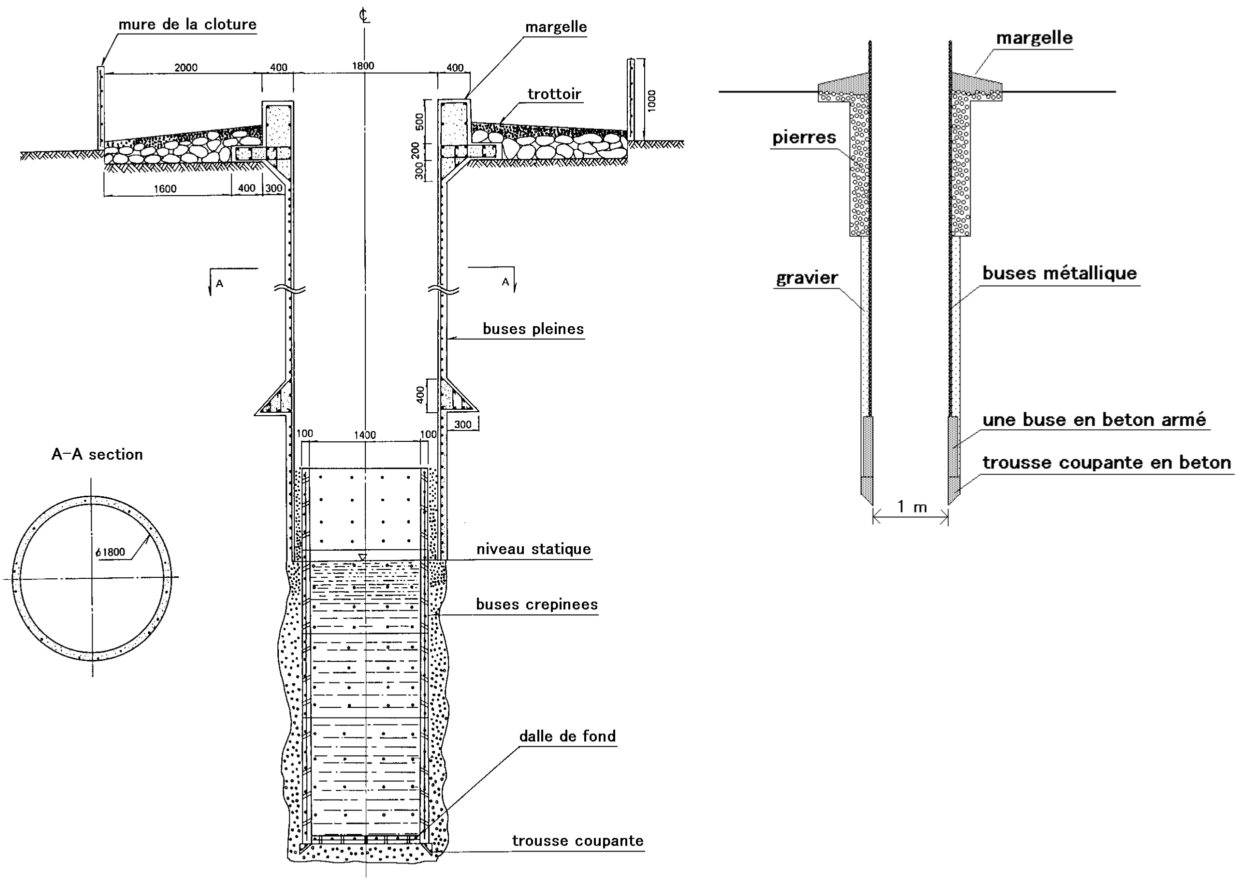
Structure of collecting well

(3) Structure of large-diameter well

For a small-scale subsurface dam whose minimum reservoir level is shallow, a large-diameter well that can be created manually without special excavators may be suitable. This well is about 1 to 2 m in diameter and a reinforced concrete or colgate pipe is used as its casing. In place of a pump, a bucket can be used to save costs. By preparing several pulleys above the well, many people can pump water at the same time. In West Africa, wells up to 40 to 50 m deep have been excavated. However, deep excavation is not possible because construction deeper than the groundwater surface requires water replacement and increases the risk of hole wall collapse. Therefore, the well should be constructed when the groundwater level is low in the dry season before cut-off wall construction for a dam. For a soft stratum, excavation with shovel is possible. For a hard stratum, a pick hammer with compressor or dynamite blasting is used. Figure 5.3.10 shows the structure of a large-diameter well.

Figure 5.3.10 Structure of Large-diameter Well (Clark, 1988, etc.)





(4) Structure of underdrain

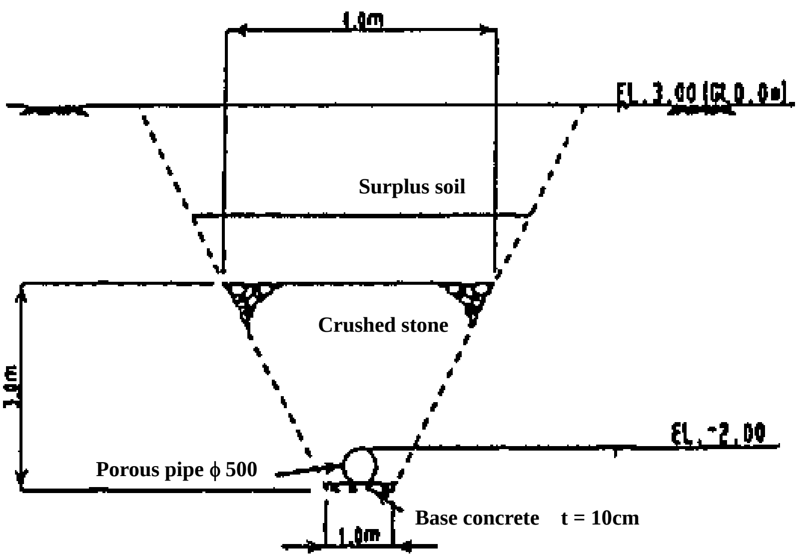
An underdrain for intake has basically the same structure as one for drainage. Therefore, the design of the underdrain is described in detail in “3) Underdrain” in 5.4.3, “Types and structures of drainage facilities.” This section gives examples of underdrains designed and constructed for intake.

(a) Intake trench at the Senbaru subsurface dam

Since the minimum reservoir level is shallow at the Senbaru subsurface dam, an underdrain (intake trench) will be installed in parallel with the dam axis and connected to the trunk headrace of the upstream and downstream direction installed in the reservoir area for intake.

For the intake trench, the ground will be dug about 5 deep from the surface to the minimum reservoir level and a pipe 50 mm in diameter with hole will be inserted. The area above the pipe will be backfilled with crushed stones (Figure 5.3.11). The planned extension of the intake trench is 3 km. For maintenance after installation, a manhole will be installed every 200 m on the trunk headrace.

Figure 5.3.11 Sectional View of Intake Trench at the Senbaru Subsurface dam



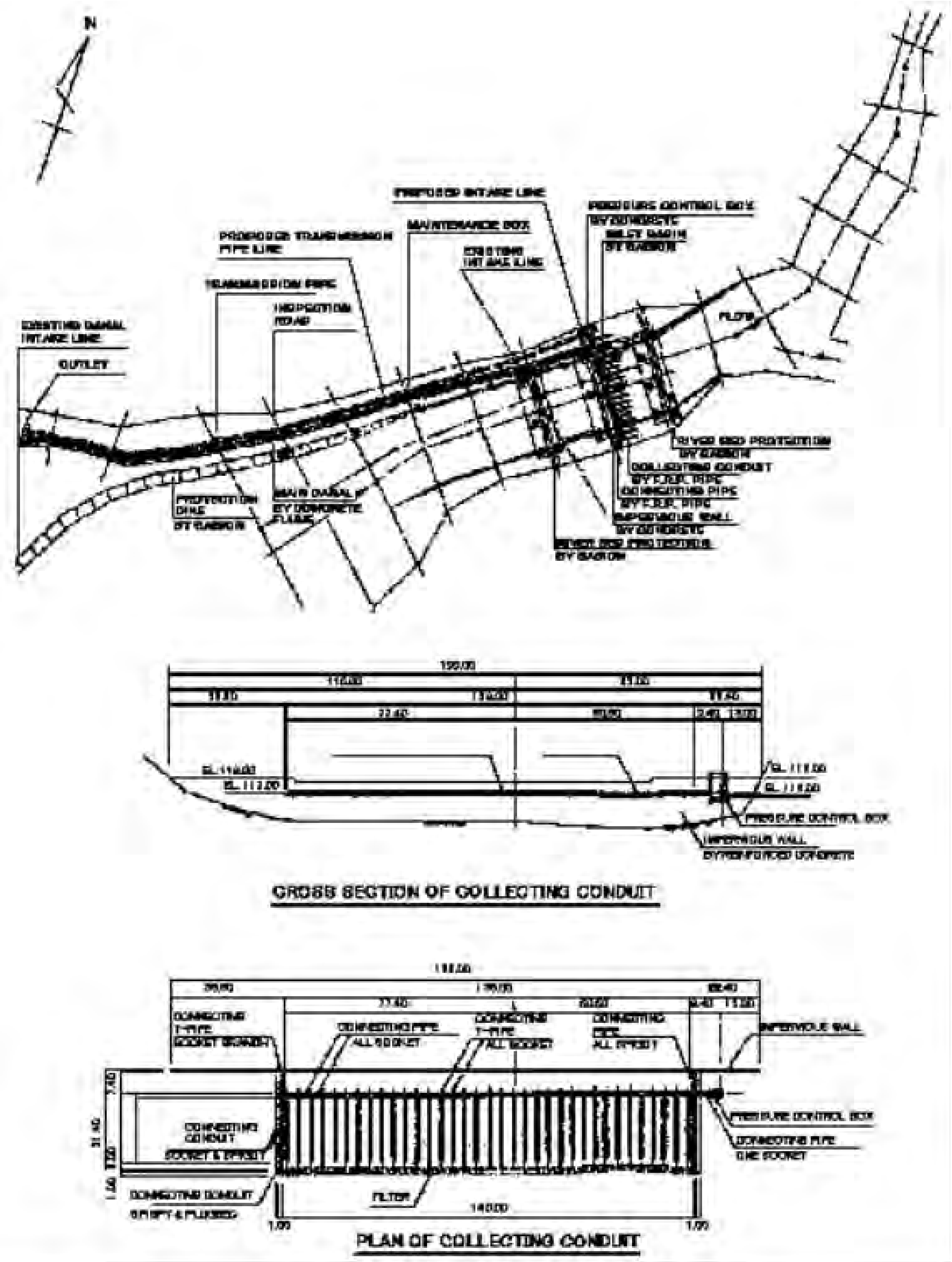
(b) Case of intake facilities for open-cut subsurface dams in the Philippines

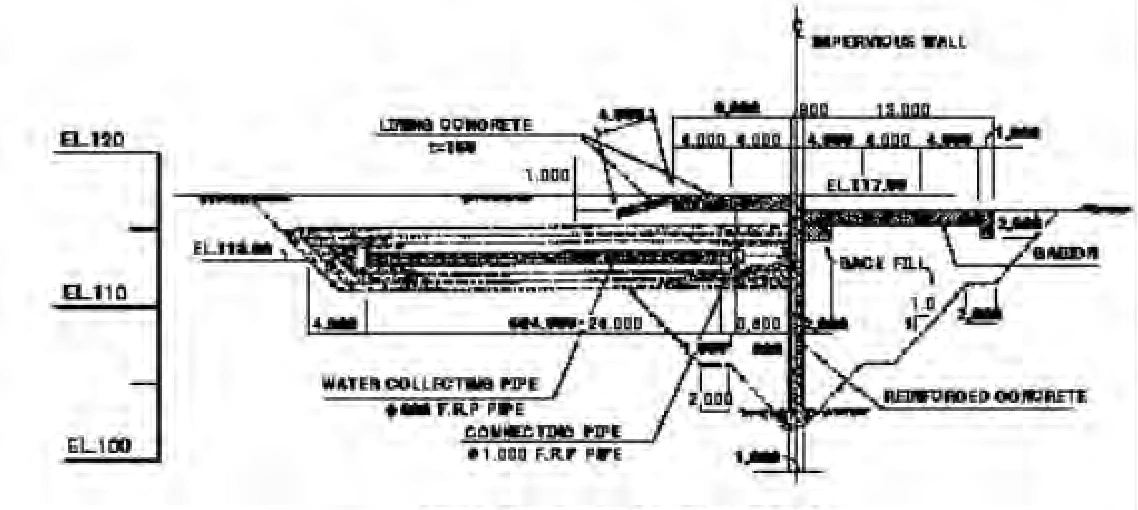
In Diplo District and Principal District of Panagsinan, the Philippines, 35 reinforced plastic pipes 60 to 80 cm in diameter with hole were installed at 4-m intervals in the upstream direction from the groundwater-impervious wall in a comb shape to collect water for the subsurface water collecting underdrain. The underdrain length per pipe is 20 to 24 m. Three filter layers were installed around each collecting pipe. The filters are a coarse-grain filter (grain size: 40 to 60 m), a medium-grain filter (grain size: 15 to 40 mm), and a fine-grain filter (grain size: 2 to 15 mm) outward from the pipe (Figure 5.3.12).

To prevent an unnecessary head difference during water transmission downstream from the groundwater collecting underdrain, a surge tank was installed in the middle of the pipe to isolate the upstream and downstream pressures.

For riverbed excavation, intensive work needed to be done in the dry season with no water flow. To prevent water permeation during work, a drain pit was excavated downstream from the construction site and an open channel was excavated downstream from the pit to drain the permeated water.

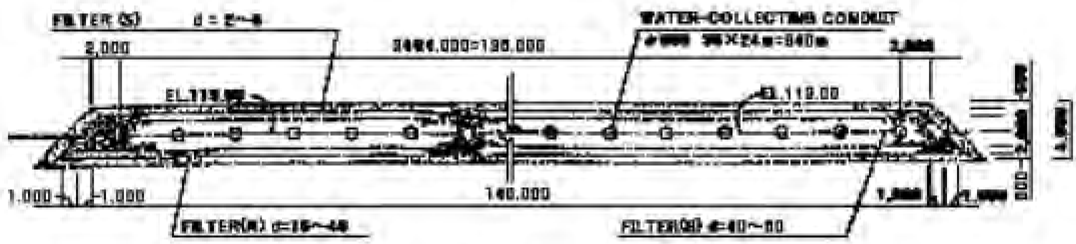
Figure 5.3.12 Structure of Intake Facilities in Principal District





CROSS SECTION OF IMPERVIOUS WALL

VERTICAL SECTION OF WATER-COLLECTING CONDUIT

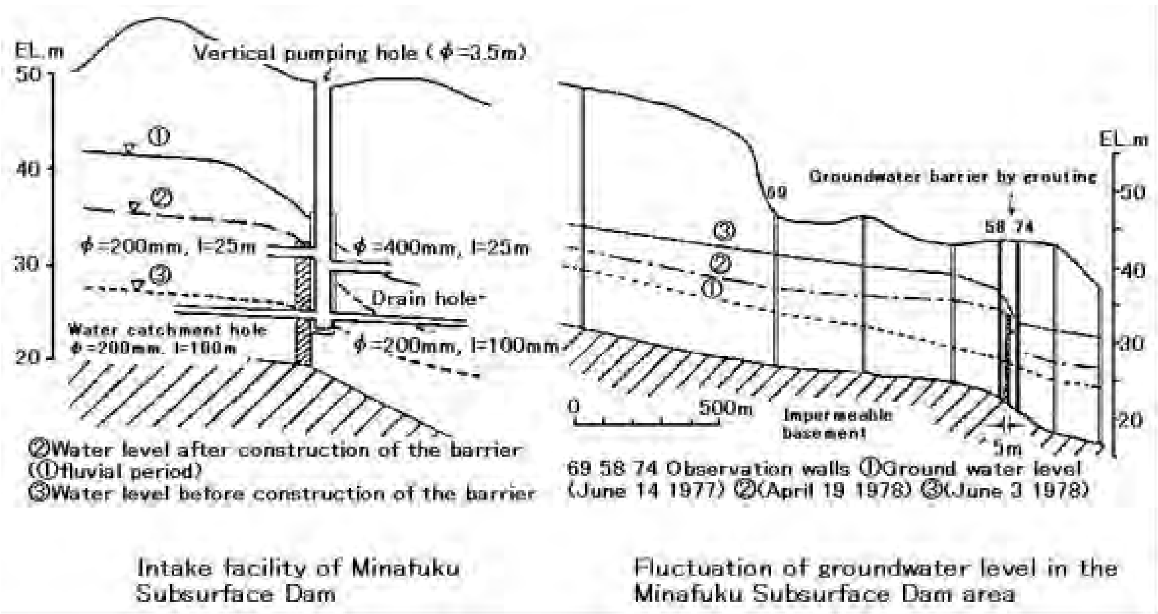


CROSS SECTION OF WATER-COLLECTING CONDUIT

(5) Structure of collecting adit

At the Minafuku subsurface dam, a collecting vertical hole was bored downstream of the cut-off and a collecting audit was installed from inside the vertical hole through the cut-off wall to the reservoir layer. In the downstream direction, a drain adit with valve at the portal was also installed for drainage (Figure 5.3.13).

Figure 5.3.13 Structure of Intake Facilities at the Minafuku Dam



5.4 Drainage facilities

5.4.1 Basic policy of drainage

Drainage facilities are installed to prevent a groundwater level rise accompanying subsurface dam construction from producing adverse effects on land use and the environment in the reservoir area (including catchment areas around the reservoir area where the groundwater level is assumed to rise).

A subsurface dam comprises facilities to store groundwater by a cut-off wall installed underground and prevent disaster by destruction of the cut-off wall. By raising the groundwater level, however, the cut-off wall may cause or promote inundation or poor drainage in the catchment area. Therefore, it becomes necessary to prevent the groundwater in the reservoir area from increasing beyond a certain level.

Reducing the dam height is the preferred method for draining surplus water quickly using only a dam crest overflow for keeping the reservoir level low. If the dam height is raised to secure the necessary reservoir capacity, however, drainage facilities are often needed in the reservoir area. They are also necessary if the groundwater level is substantially high, as in the case of a subsurface dam of saltwater infiltration prevention constructed along the coastal area.

As a rule, the necessity of drainage facilities shall be judged by forecasting the trend of groundwater level under a heavy rainfall from the results of flood analysis. This judgment may also be possible by comparing a sectional area of water passage before installation of the cut-off wall with that of overflow after installation and checking the ground permeability around the overflow section.

5.4.2 Location and scale of drainage facilities

(1) Determining the critical high water level

The critical high water level means the normally allowable highest water level in the reservoir area of a subsurface dam. This level is determined as a water level not disturbing normal land use in a low-altitude place in a reservoir area where subsurface dam construction reduces the difference of altitude between the reservoir level and the surface.

At the Sunagawa subsurface dam, the reservoir area is mainly fields. There are no large structures. We see houses but no subsurface structures, such as basements. Since bedrock is distributed near the surface, foundation works or subsurface uses reaching deep under the ground can also hardly be assumed in the future. Therefore, the critical high water level of the Sunagawa subsurface dam was set to 3 m below the surface not to damage agricultural or subsurface construction of about one floor level by inundation or moisture.

(2) Determination of the drainage reference year for design

When studying the dam height and drainage facilities for a subsurface dam, a specific year of a certain precipitation is assumed and the reservoir level after subsurface dam construction is forecast as a change from the precipitation. To make the reservoir level lower than the critical high water level in the reference year, the dimensions of necessary drainage facilities are determined. If high precipitation is assumed, the reservoir level rises accordingly. To keep the reservoir level lower than the critical high water level, the dam height should be made lower or the drainage facilities should be made greater. This specific year is called the drainage reference year for design.

From precipitation data of about 30 years in the past, an appropriate groundwater flow model of each year is created to estimate the reservoir level. A year becomes the drainage reference year for design if the estimated reservoir level satisfies either of the following conditions:

1. High water level that is reproduced once in N years (N-year probability)
2. Highest water level estimated from past rainfall observation data (Past maximum value)

N may be about 30 or 50.

At the Sunagawa subsurface dam, 50-day precipitation closely correlates with the actual groundwater level fluctuation. Therefore, annual precipitation data of up to 50 days was obtained for the past 30 years and the probability was calculated using the Iwai method and the Gumbel method. The greatest 50-day precipitation in the 30 years was recorded in 1966. The Iwai method indicated 287-year probability and the Gumbel method indicated 76-year probability. This precipitation was greater than the 50-year probability. Considering that no floods are allowable, 1966 is set as the drain reference year for design at the Sunagawa subsurface dam.

(3) Flood analysis

The rainfall pattern in the drain reference year for design is given to the groundwater flow model incorporating a subsurface dam for flood analysis to forecast the groundwater level and the groundwater flow rate. From the results, a range exceeding the critical high water level in the reservoir area is set as the range of drainage. Then, the conditions of drainage are determined, including the drainage discharge necessary to keep from exceeding the critical high water level.

The groundwater flow model used for flood analysis should have the following functions from ① to ③ and be able to reproduce a groundwater surface shape in detail. This model may double as one for intake analysis.

1. Logical grounds for the calculation of extrapolation are clear.
2. A subsurface dam can be incorporated into the model to forecast the groundwater level fluctuation after subsurface dam construction.
3. The water level at an arbitrary point in the range of analysis including the reservoir area can be evaluated.

As the groundwater flow model, a simple model such as a series tank model can be used for rough analysis in basic planning. For detailed analysis to design facilities, the reservoir area is divided into smaller segments and modeled using the finite element method.

To satisfy the necessary drainage discharge and other conditions in the range of drainage, the types, structures, and scales of drainage facilities are studied. The assumed functions of drainage facilities are incorporated into the groundwater flow model to see that the reservoir level in the drain reference year for design becomes equal to or lower than the critical high water level. Then the dimensions of drainage facilities are determined in the end.

5.4.3 Types and structures of drainage facilities

The drainage facilities for a subsurface dam shall have necessary functions to prevent the groundwater level in the reservoir area in the drainage reference year for design from exceeding the critical high water level.

The drainage facilities for a subsurface dam mainly use the following systems:

1. Cut-off wall overflow
2. Underdrain
3. Open ditch or open ditch with underdrain
4. Adit (drainage tunnel)
5. Pumping (drainage well)

The construction types and places of drainage facilities are determined from the necessary drainage discharge in the drain reference year for design, the reservoir level fluctuation pattern, and the range of drainage by also considering the surface shape (altitude) and the ground permeability near the aquifer and surface.

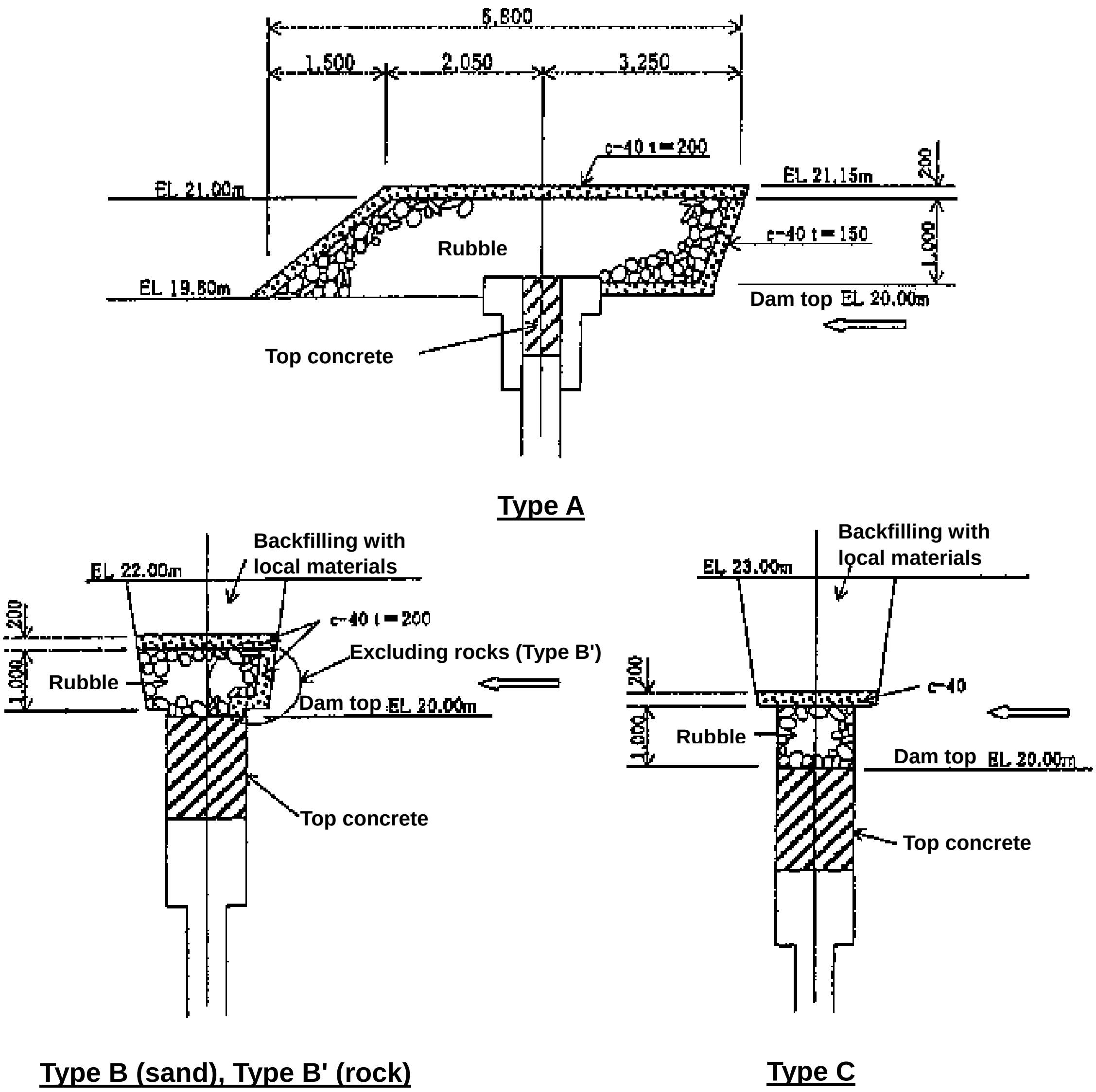
(1) Structure of cut-off wall overflow section

To drain surplus water immediately downstream from a subsurface dam, it is preferable to secure an adequate sectional area of water passage for overflow on the dam axis to increase the dam crest overflow rate. When reducing the overflow section by cut-off wall construction, check by flood analysis that an adequate amount of water can be drained. Install drainage facilities separately if the cut-off wall construction method and topographical conditions make it difficult to secure good permeability at the overflow section or impossible to reserve an adequate overflow section.

If the open-cut method or the diaphragm wall method by grooved excavation is adopted, the permeability of the excavated face must not be impaired to ensure good permeability in the overflow section, and the overflow section needs to be backfilled with permeable materials.

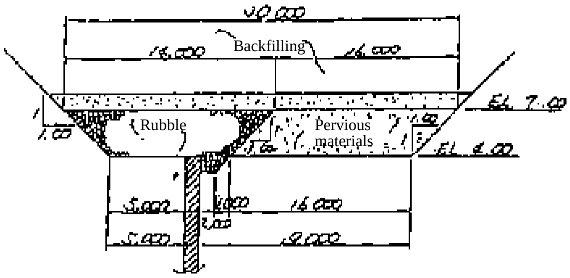
The cut-off wall for the Kikai subsurface dam was constructed by the deep mixing method. After rubble was placed in the section one meter from the dam crest, the overflow section was backfilled with field materials available on the site. A layer of crushed stones 0.2 m thick (φ40 mm) was sandwiched between the rubble and field materials to prevent fine particles flowing down from blinding the overflow section (Figure 5.4.1).

Figure 5.4.1 Structure of the Overflow Section at the Kikai Subsurface dam

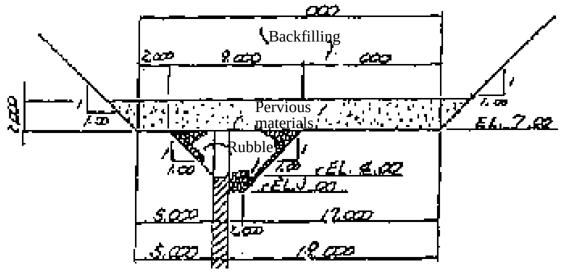


If there is only a small difference of altitude between the ground and the dam crest, the cut-off wall construction face and the top face can almost be matched by digging. When restoring the original conditions, the drainage capacity of the overflow section can be increased by backfilling around the overflow section with permeable materials. At the Komesu subsurface dam, a section about 25 to 30 m wide will be backfilled with rubble and permeable field materials as shown in Figure 5.4.2.

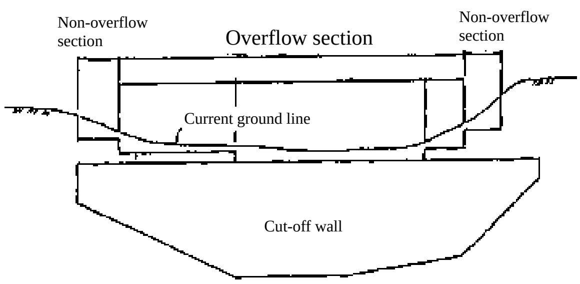
Figure 5.4.2 Sectional View of the Overflow Section at the Komesu Subsurface dam



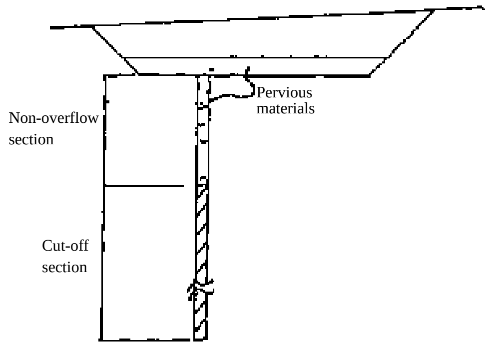
Overflow section Type 1



Overflow section Type 2



Standard sectional view of overflow section



Standard sectional view of non-overflow section

(2) Design and structure of underdrains

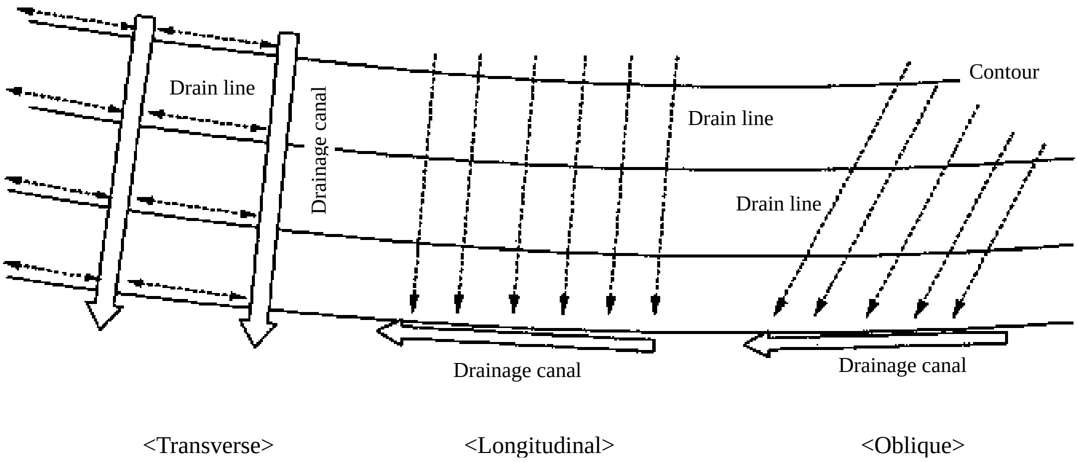
To calculate the necessary drainage discharge through underdrains, the general planned drainage discharge by drainage analysis is divided by the drainage area. To ensure this drainage discharge, the underdrain installation range, the distance between underdrains, and the installation depth are determined.

An organization of discharge through underdrains consists of sub-lateral drains to collect surplus groundwater in the range of drainage, and collecting drains to collect groundwater from the sub-lateral drains and allow it to flow to surface drainage canals. Depending on the placement of drain lines against contour, the underdrain (sub-lateral and collecting drains) arrangement can be classified into the following types (Figure 5.4.3):

1. Transverse: Drain lines are arranged almost along the contours and are led to the drainage canals flowing at an angle.
2. Longitudinal: Drain lines are arranged vertically against the contours.

3. Oblique: Drain lines are arranged at an angle against the contours.

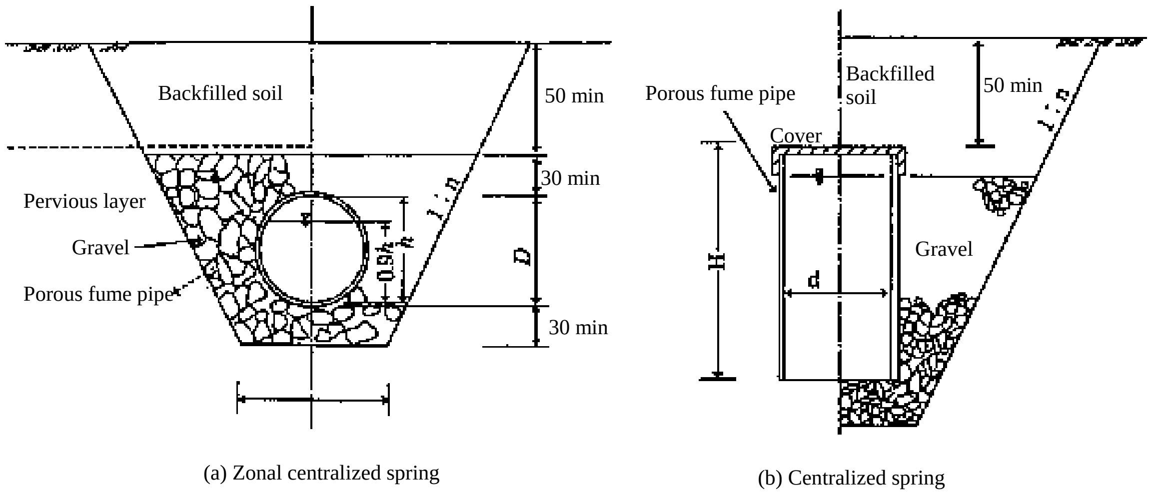
Figure 5.4.3 Arrangement of Underdrains



The transverse type can catch water easily because the drains are orthogonal against the groundwater flow direction. However, since the flow direction changes by 90° at the junction with a collecting drain or a drainage canal, it becomes difficult for the groundwater to flow down if the sub-lateral drain does not have a gradient. The longitudinal type allows groundwater to flow down easily through the processes of collection and drainage. However, since the drain lines are parallel with the groundwater flow direction, quite a distance is necessary for a sub-lateral drain to catch groundwater well.

As Figure 5.4.4 shows, a sub-lateral drain consists of an absorption pipe and filter materials. The diameter of the absorption pipe is determined by the procedure shown in Figure 5.4.5.

Figure 5.4.4 Structure of Sub-lateral Drain



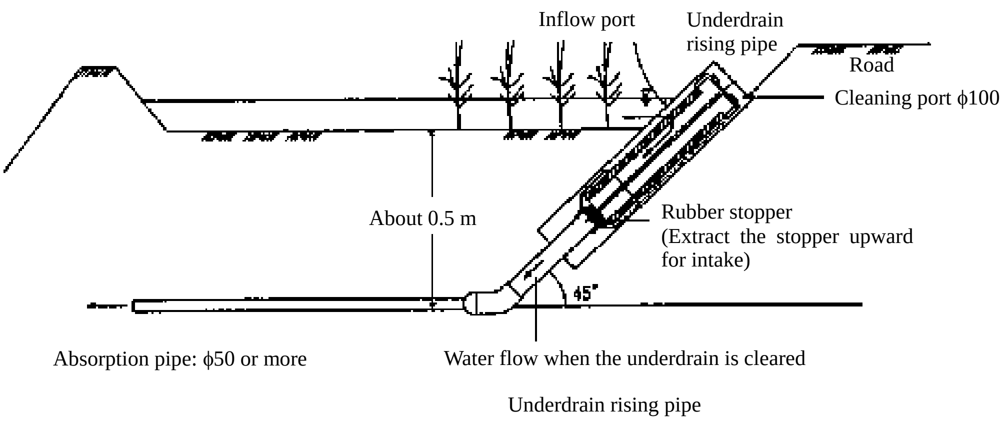


Figure 5.4.5 Determining the Diameter of the Absorption Pipe

START

↓

Determine the depth of drain port and the burial depth of underdrain pipe

↓

Determine the absorption pipe length and the laying gradient

↓ ← Planned underdrain drainage discharge D
Underdrain interval S

Calculate the absorption pipe diameter

↓

Estimate and evaluate mean flow velocity

↓

Determine the absorption pipe diameter

Various formulas have been proposed for calculating drainage discharge through a sub-lateral drain. Two of them are shown below (see Figures 5.4.6 and 5.4.7).

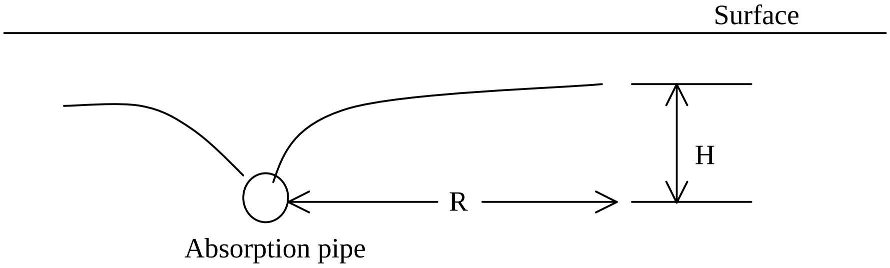
$q = 2\alpha k H_1/\ln(R/r)$ $\alpha = \pi/2 + H_1/R$ (Radian)

q: Amount of collection per unit length of sub-lateral drain, r: Radius of absorption pipe,

H_1: Depth of sub-lateral drain axis in aquifer

R: Radius of influence area (Formula of underdrain when a deep impervious layer exists)

Figure 5.4.6 Calculation of Drainage Discharge Through Sub-lateral Drain (1)

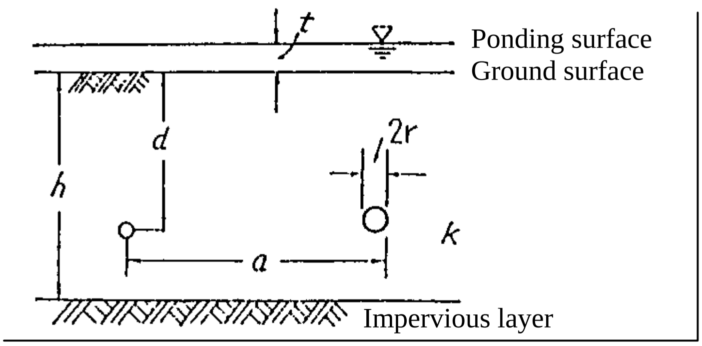


$q = 2\pi k\,(t + d - r)/\ln\{[\tan(\pi(2d - r)/(4h))][\cot(\pi r/(4h))]\}$ $a/h \geq 1$

$q = 2\pi k\,(t + d - r)/\ln\{[\sinh(\pi(2d - r)/a)][\mathrm{cosech}(\pi r/a)]\}$ $a/h < 1$

q: Amount of collection per unit length of sub-lateral drain, h: Top depth of impervious layer, t: Depth of surface ponding (= 0), k: Hydraulic conductivity (cm/s), r: Radius of absorption pipe, d: Depth of absorption pipe, a: Interval of absorption pipe

Figure 5.4.7 Calculation of Drainage Discharge Through Sub-lateral Drain (2)



The sub-lateral drain interval is generally 6 to 30 m, wide for high-permeability ground and narrow for low-permeability ground. The underdrain pipe laying gradient is greatly dominated by the topography in the drainage area, the depth of drainage canal at the end, and the burial depth of underdrain pipe. In general, the absorption pipe laying gradient is about 1/100 to 1/1,000.

The diameter of underdrain pipe is selected to satisfy the in-pipe flow velocity and the planned drainage discharge per underdrain. Considering the reduction of the pipe cross section by earth sedimentation and scale deposition, it is preferable to realize the planned flow rate at a depth of about 70% of the pipe diameter. The in-pipe flow velocity and the drainage discharge can be calculated using the Manning formula (see Table 5.4.1).

$V = 1/n \times (r)^{2/3} \times I^{1/2} \times \beta \qquad \beta = [(\pi-\theta+\sin\theta\times\cos\theta)/2/(\pi-\theta)]^{2/3}$

$q = 1/n \times (r)^{8/3} \times I^{1/2} \times \alpha \qquad \alpha = (\pi-\theta+\sin\theta\times\cos\theta)^{5/3}/[2\times(\pi-\theta)]^{2/3}$

V: In-pipe flow velocity (m/s), r: Radius of pipe (m), I: Laying gradient,

q: Drainage discharge (m^3/s),

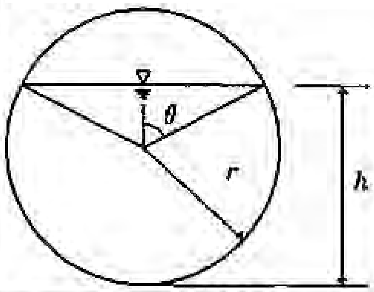
n: Coefficient of roughness of pipe (synthetic resin pipe (corrugated inside): 0.016, synthetic resin pipe (smooth inside): 0.012, porous clay pipe: 0.013, porous clay pipe (pottery pipe): 0.012)

Table 5.4.1 Flow Rate and Flow Velocity Calculation Table for Underdrain Pipe

$$Q=\frac{1}{n}\times r^{\frac{8}{3}}\times I^{\frac{1}{2}}\times\alpha$$

$$V=\frac{1}{n}\times r^{\frac{2}{3}}\times I^{\frac{1}{2}}\times\beta$$

$h/2r$	α	β	Remarks
0.50	0.98954	0.62996	Q = Flow rate (m^3/s)
0.55	1.15917	0.65473	r = Radius of pipe (m)
0.60	1.32962	0.67558	n = Coefficient of roughness
0.65	1.49699	0.69251	I = Gradient
0.70	1.65696	0.70541	V = Flow rate (m/s)
0.75	1.80468	0.71404	
0.80	1.93488	0.71799	
0.85	2.03932	0.71653	
0.90	2.10929	0.70827	
0.95	2.12655	0.68980	
1.00	1.97907	0.62996	



Note: $\alpha=\dfrac{(\pi-\theta+\sin\theta\cdot\cos\theta)^{5/3}}{[2\ (\pi-\theta)]^{2/3}},\quad \beta=\left[\dfrac{\pi-\theta+\sin\theta\cdot\cos\theta}{2\ (\pi-\theta)}\right]^{2/3}$

An absorption pipe shall be selected from ones made of a material having a necessary cross section for water passage, strength, endurance, and absorption performance and featuring high installation efficiency at low costs. For subsurface dams, underdrains made of rigid PVC are popular.

The filter material is critical in that it affects the collection performance of an underdrain and the endurance against blinding. As the filter material, coarse gravels or natural sand satisfying the following filter conditions is preferable. For underdrains of subsurface dams, crushed stones of a grain size from about 20 to 40 mm are popular as filter material. Gravels of a large grain size are not favorable for pipe protection. The preferable thickness of a filter material is 50 cm or more on the top of an absorption pipe.

$$\frac{\text{15\% grain size of filter material}}{\text{15\% grain size of filter-protected material}} > 5 \qquad \text{(For sufficient filter permeability)}$$

$$\frac{\text{15\% grain size of filter material}}{\text{85\% grain size of filter-protected material}} < 5 \qquad \text{(For no filter blinding)}$$

$$\frac{\text{85\% grain size of filter material}}{\text{Pipe bore diameter}} > 2 \qquad \text{(For coarseness of filter material)}$$

The burial depth of an absorption pipe shall be deeper than the depth of the critical high water level plus the difference between the groundwater level and the water level in the absorption pipe. For example, if the critical high water level is GL. –3 m and the water level difference between the groundwater level and the water level in the absorption pipe is 0.5 m, the burial depth of the absorption pipe shall be GL. –3.5 m or deeper.

The end of an underdrain is connected to a river or open channel. For drainage from the end under a natural flow, an adequate difference of water level is preferable between the end height of the drain and the water level in the river or open channel. If the river water level is high due to heavy rainfall and adequate drainage discharge cannot be secured under a natural flow, install a gate between the underdrain end and the river or open channel with a pump for forced drainage.

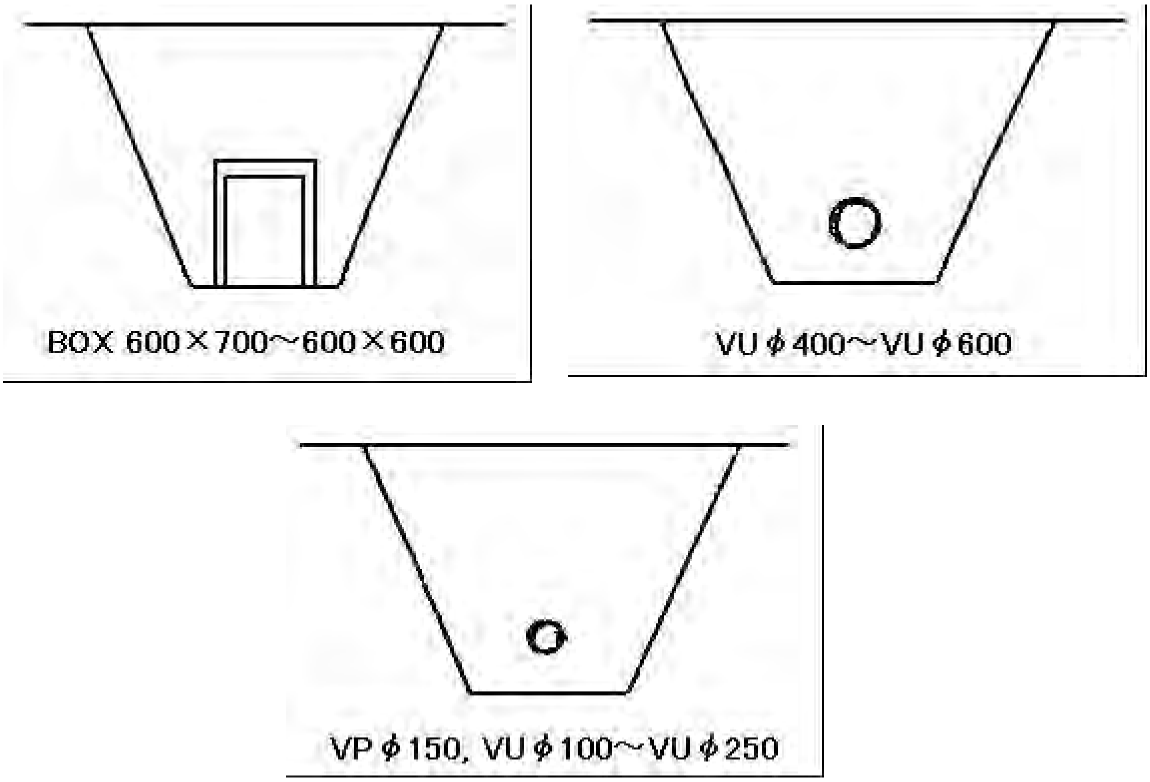
Install a rising pipe at the upstream end of a sub-lateral drain. Pour surface water in from the surface or insert a hose for washing inside the underdrain.

For the Kikai subsurface dam, drainage facilities of the underdrain type were adopted. Table 5.4.2 gives the dimensions of underdrains at the Kikai subsurface dam and Figure 5.4.8 shows the structure.

Table 5.4.2 Underdrains at the Kikai Subsurface dam

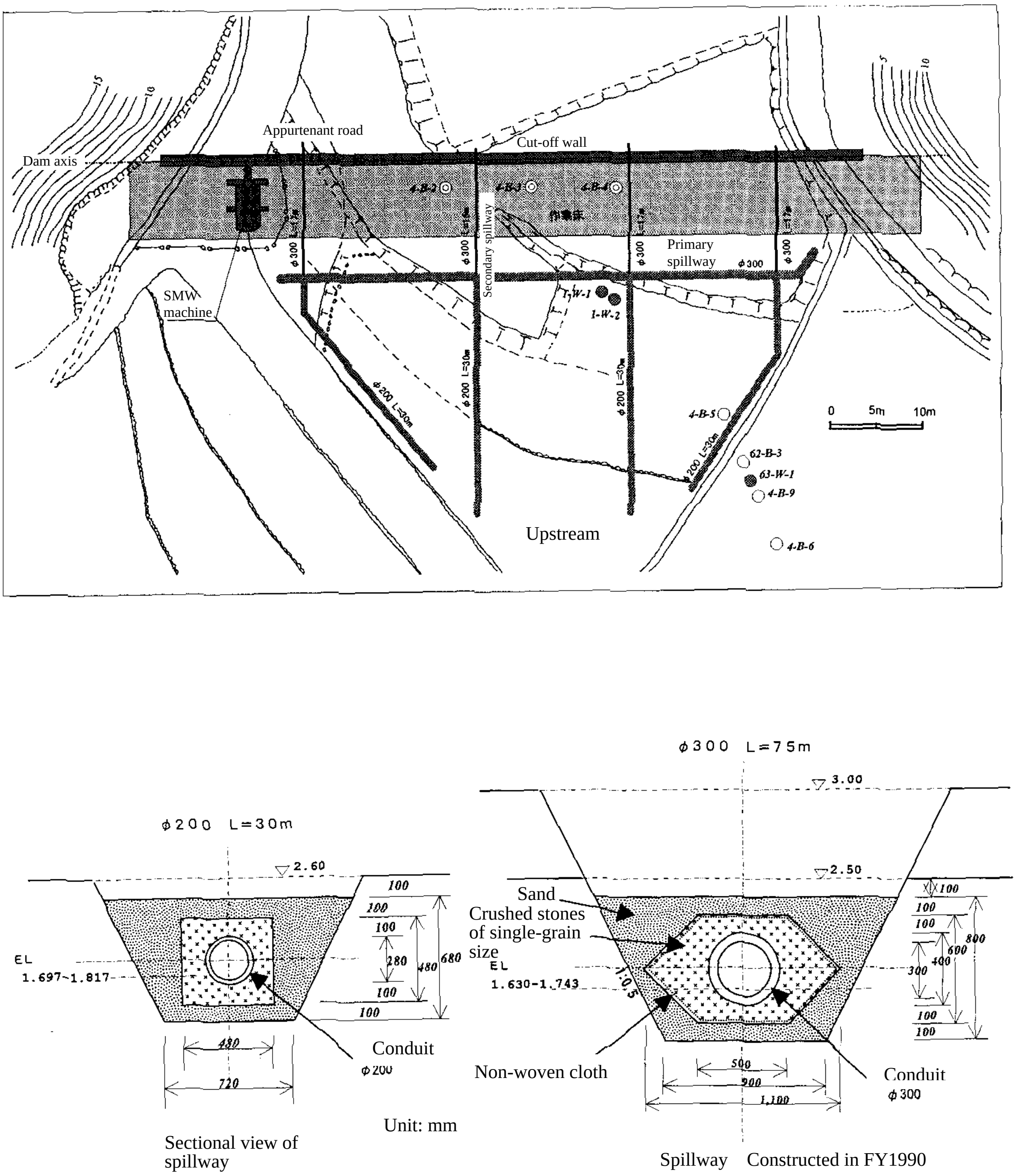
Type	Dimensions	
Sub-lateral drain	Installation depth: 3.5 m or deeper from the surface (critical high water level - 0.5 m) Filter material: Crushed stones (maximum grain size: 20 mm or less) VP pipe: φ150 mm, L = 3,380 m VU pipe: φ100 to 250 mm, L = 3,865 m	Drain flow rate Left bank: 0.180 m^3/s Right bank: 0.068 m^3/s
Collecting drain	Box culvert: 0.6×0.6 – 0.7, L = 493 m VU pipe: φ400 to 600 mm, L = 1,819 m	

Figure 5.4.8 Structure of Underdrain at the Kikai Subsurface dam



At the Nakajima subsurface dam, a groundwater collecting underdrain (primary spillway) was installed in the alluvial swamps storing groundwater as a reservoir to avoid dam construction from causing damage by moisture or ponding. In addition, an underdrain (secondary spillway) was installed across the dam axis to collect groundwater and allow the collected groundwater to overflow from the top of the cut-off wall. For these underdrains, porous concrete pipes 200 to 300 mm in diameter were used and the surroundings backfilled with crushed stones and sand as filter materials (Figure 5.4.9).

Figure 5.4.9 Underdrains at the Nakajima Subsurface dam



At the Senbaru subsurface dam, underdrains are planned as drainage facilities. Table 5.4.3 gives the dimensions of underdrains at the general implementation design stage.

Table 5.4.3 Dimensions of Underdrains at the Senbaru Subsurface dam

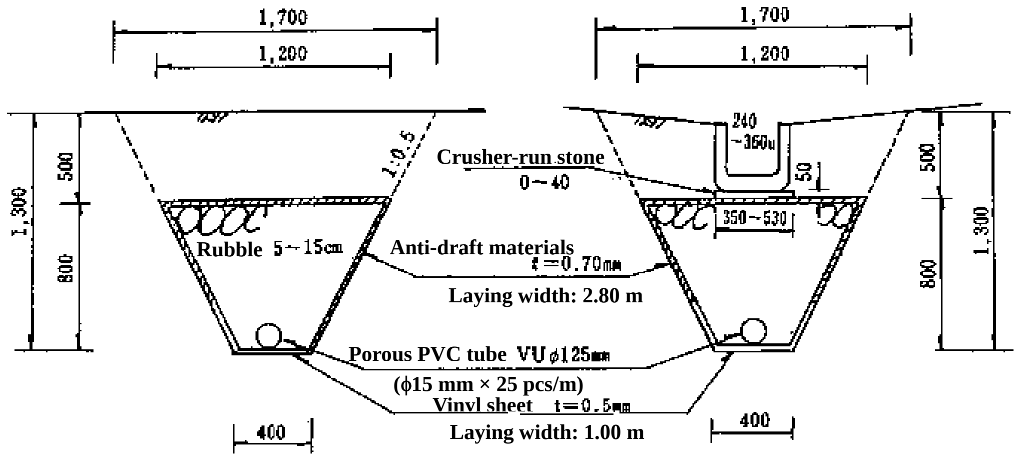
Item	Dimensions
Forecast ponding range	900 m × 500 m
Critical high water level	GL. –0.5 m (cultivated layer)
Planned drainage discharge	86,200 m^3/day = 192 mm/day (50-year probability drainage discharge)
Underdrain installation interval	30 m
Laying depth	Mean altitude: 1.5 m (GL. –1.5 m)
Underdrain pipe	Rigid PVC tube 100 mm in diameter (coefficient of roughness: 0.012)
Underdrain discharge capacity	245 mm/day = 6.67×10^{-5} m^3/sec per meter of underdrain
Laying gradient	1/680
Necessary extension	15,300 m

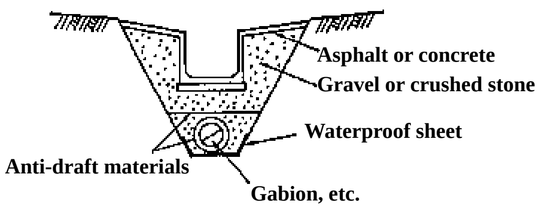
(3) Open ditch with underdrain

The open ditch with underdrain type has a two-storey structure integrating a drainage canal and a underdrain to efficiently eliminate surface water and groundwater at the same time. Figure 5.4.10 shows a general structure of the open ditch with underdrain type.

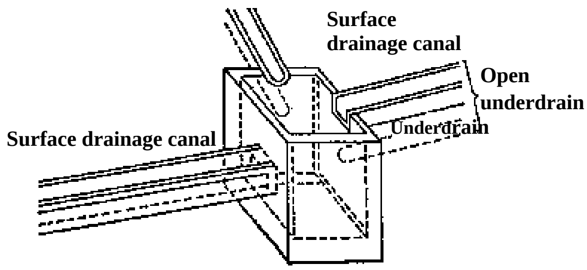
Figure 5.4.10 Structure of the Open Ditch with Underdrain Type

Blind underdrain Open underdrain

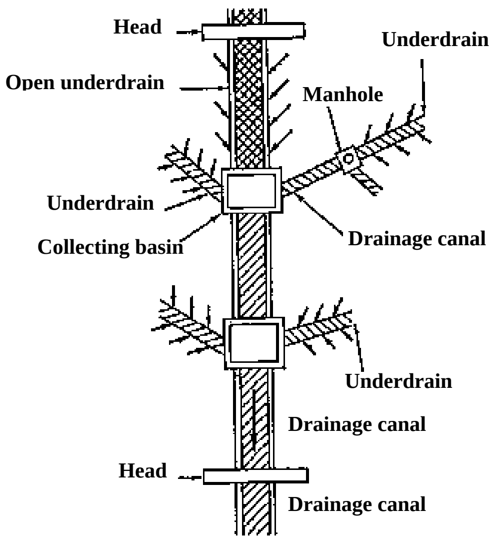




Sectional view of open underdrain



Structure of collecting basin



Arrangement of underdrains

(4) Adit (drainage tunnel)

A subsurface tunnel is constructed in a reservoir area and groundwater flowing into the tunnel is drained. Although the effect is significant, the geological conditions of the ground to be excavated and the groundwater status needs to be considered and the construction costs are generally high. The adit method should be discussed on the assumption of use with intake facilities.

At the Minafuku subsurface dam, a collecting adit collects groundwater and allows it to flow down into a vertical hole to drain through a discharge tunnel installed downstream (Figure 5.3.13).

(5) Pumping (drainage well)

Drainage wells are constructed and water is drained using pumps. Water can be intensively drained from a necessary location and transported even through a pipeline. If there is an intake well in the necessary location, it can be used for drainage.

Pumping carries high costs for running and maintaining the drainage pumps. In addition, high-level management is necessary for starting and stopping draining based on a forecast of the groundwater level. This method is applicable to a limited area of drainage and may be more advantageous than other drainage methods if the planned drainage discharge is comparatively small.

5.5 Management Facilities

5.5.1 Types of management facilities

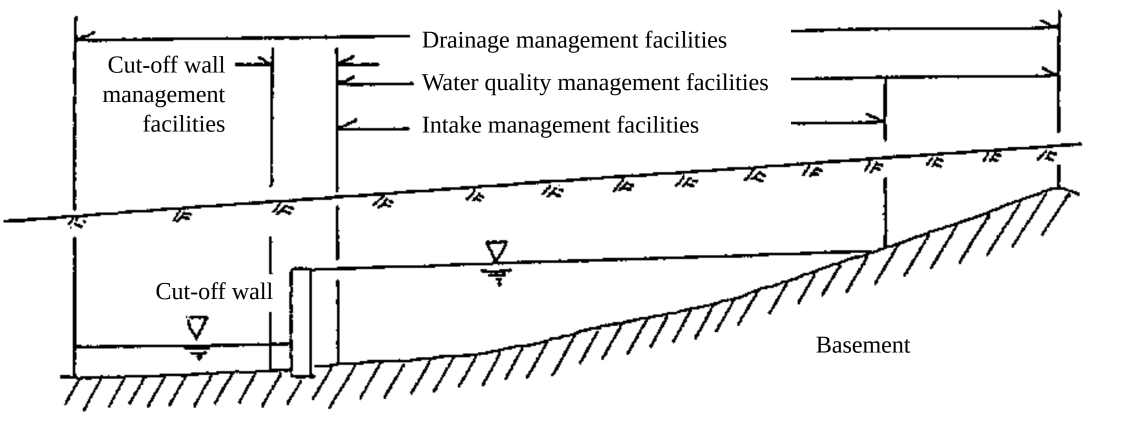
For subsurface dam management, collect and analyze data on precipitation and other meteorological conditions and the groundwater quality to check the dam functions, monitor the reservoir status, and take measures as required.

To manage the functions of a subsurface dam, the following facilities are installed:

- Cut-off wall operation and maintenance facilities
- Reservoir operation and maintenance facilities (intake, drainage, etc.)
- Water quality operation and maintenance facilities (salinity, etc.)

For monitoring the reservoir status and operating the subsurface dam, groundwater level data is indispensable. Figure 5.5.1 shows the range of groundwater level observation.

Figure 5.5.1 Range of Groundwater Level Observation



The groundwater level can be monitored by observing the water level in a well or borehole (observation hole) of groundwater observation facilities. By using an observation hole, groundwater may be sampled for water quality analysis. The arrangement and number of observation holes are determined by the purpose of observation, the topological and geological characteristics of the subsurface dam catchment area, and the hydrological characteristics of the groundwater.

5.5.2 Cut-off wall operation and maintenance facilities

The cut-off wall and reservoir area of a subsurface dam do not collapse because they are underground. Cut-off wall management is to monitor the cut-off wall for the deterioration of imperviousness and maintain its functions by taking appropriate measures.

Damage by artificial excavation, cracking by earthquake, etching by groundwater, and seepage failure deteriorate the imperviousness of the cut-off wall and cause local water leakage. At an afflux subsurface dam, the groundwater level consequently falls directly upstream of the damaged section and rises directly downstream. At a subsurface dam of saltwater infiltration prevention, the groundwater salinity changes between the upstream and downstream of the damaged section. Therefore, observation holes are prepared directly upstream and downstream of the cut-off wall and the groundwater level and groundwater salinity (electric conductivity) are observed periodically or in the case of an earthquake.

The observation holes are constructed at nearly equal intervals upstream and downstream of the dam axis. At the construction of observation holes, assume the scale of leakage to be detected and estimate a leakage-attributable water level fall at the upstream of the dam axis from the difference of water level between the upstream and downstream of the dam axis and the permeability of the aquifer. From the water level drop and the observation error, assume a detectable water level fall and determine the observation hole interval. Reducing the observation hole interval will increase the facility installation costs and the observation work, but will make it comparatively easy to find and locate smaller places with water leakage.

Observation holes may be constructed densely in the following possible places of leakage:

- A place of low cut-off wall quality because holes were frequently bent at cut-off wall construction
- A place of dam axis bending where groundwater flow tends to be congested
- The final cut-off section or where the basement top is especially deep
- A place of special construction method, such as cavity processing
- A joint of cut-off wall construction methods if different construction methods are used
- A basement fault where water from the basement may leak out

In Miyako District, survey boring was conducted at many points along the dam axis and in the reservoir area to check the basement depth when designing the cut-off wall and intake facilities. Some of these boreholes were left as observation holes to locate damage of the cut-off wall. By considering the relationship between the amount of leakage and water level fall and also the observation error, the minimum detectable water level fall was set to 3 cm. If the observation hole interval is within 200 m, leakage of the assumed scale will be detectable.

The groundwater level can be observed continuously with a water level recording gauge or manually with a portable water level gage. For cut-off wall management, manual observation is adequate because there are many observation points, it takes time until leakage is reflected in the water level distribution, and leakage does not produce downstream damage.

5.5.3 Reservoir operation and maintenance facilities

Subsurface dam reservoir management can be divided into intake management and drainage management and covers the reservoir level, intake, drainage discharge at a flood, and leakage. These items are managed with precipitation and other meteorological data and also groundwater level data. Since the groundwater flow rate cannot be measured directly, it must be estimated from groundwater level measurement data.

To simplify the management of 171 pumps in total, the intake management facilities in Miyako District are divided into group pumping stations for controlling 5 to 15 pumps each and a central management office for administering the stations. Table 5.5.1 introduces the contents of management by the central management office and the group pumping stations.

Table 5.5.1 Intake Management in Miyako District

Operation and Maintenance Facilities	Contents of Management
Central management office	1. Accumulating, displaying, and supervising measurement data on the reservoir status and main facilities (group pumping stations, pressurizing stations, farm ponds, etc.) 2. Starting and stopping pumps at each group pumping station 3. Processing data (collecting, operating, and recording) on the reservoir level, precipitation, and amount of intake and output of data documents
Group pumping station	1. Measuring and recording the amount of intake by each pump, the water level in each well, and the pump operation time 2. Monitoring the water level in each well and the water level in each farm pond to prepare for pump use 3. Monitoring of water supply during pump operation and each well for a water level fall 4. Monitoring power reception by each pump (leakage, overload, etc.) 5. Switching the pump control place (manual control from the station or remote control from the central management office) 6. Switching the pump operation method (automatic control or manual operation) 7. Manual pump operation (start-stop and change of operation place) 8. Automatic pump control (selection of pumps to run, operation interlocked with the water level in the farm pond, etc.)

For drainage management, a system is needed to forecast the future groundwater level especially from groundwater level and precipitation data. If the drainage start water level is set low for forced drainage, the available water quantity decreases. If the level is set high, the risk of damage by flood increases. Therefore, if groundwater level fluctuations corresponding to various precipitation patterns are modeled in advance by computer simulation, additional criteria for drainage start will be available. To obtain necessary groundwater level data for drainage management, it is preferable to install observation facilities where a flood disaster is anticipated most in the reservoir area.

5.5.4 Water quality operation and maintenance facilities

The water quality operation and maintenance facilities monitor and control the groundwater quality of a reservoir to maintain the appropriate quality. These facilities can be classified into water quality observation facilities and desalinizing facilities.

(1) Water quality observation facilities

The objects of water quality observation are reservoir water, groundwater in the upstream area, groundwater at the downstream of the cut-off wall, intake groundwater from the reservoir layer, and surface water in the catchment area. These waters are measured and sampled not only from observation holes but also by using intake facilities or drainage facilities. The observation holes for water quality observation are often used also for groundwater level observation.

To check the water quality by depth, several observation holes may be constructed for water quality observation and water sampling at each depth by limiting the screen position to the object depth of observation. In this case, water should be fully cut off above and below the screen.

The water quality may be observed not only manually by field measurement and sampling but also automatically by installing a self-recording device in the field. The technique and frequency of observation are determined by considering changes of the water quality assumed for the object groundwater. Since groundwater flow is generally slow, the groundwater quality does not change as dramatically as the surface water quality. Around the border of saltwater and fresh water in a coastal area, a quick pull of saltwater mass may salinize the water drastically. At a subsurface dam of saltwater infiltration prevention, therefore, the frequent or continuous observation of salinity should be allowed.

At a subsurface dam of saltwater infiltration prevention, water quality management is closely related to intake management. In other words, intake must sometimes be managed so that the salinity of intake water or reservoir water will not exceed the tolerance. For this kind of subsurface dam, a system needs to be established for monitoring the groundwater salinity in real time and reflecting any change immediately in intake management.

(2) Desalinizing facilities

The problems for a subsurface dam of saltwater infiltration prevention are saltwater mass remaining in the reservoir area after cut-off wall construction and saltwater permeating through the cut-off wall or basement during dam operation (intake). If such saltwater disturbs dam operations, desalinizing facilities should be installed to eliminate the saltwater from the reservoir area.

At the Komesu subsurface dam, wells will be constructed along the dam axis in the reservoir area to eliminate the saltwater remaining in or permeated into the reservoir area. Saltwater will then be pumped from the desalinizing wells. At the general implementation design, it was planned to install five wells of the dimensions shown in Table 5.5.2 and eliminate about 2,200,000 m^3 of saltwater remaining at the altitude of –20 to 0 m in the reservoir area.

Table 5.5.2 Dimensions of Desalinizing Well

Depth of Well	Diameter of Well	Pumping Rate (Per Place)	Pump Output	Pump Type
70 m	300 mm	0.4 m^3/min	7.5 kW	Submersible motor pump for deep well

5.5.5 Artificial groundwater aquifer charging facilities

One of the methods for effective groundwater use is to charge groundwater artificially. In other words, dead runoff water is permeated into the ground by using artificial groundwater aquifer charging facilities to increase the available groundwater. Groundwater can be charged by the following methods:

Table 5.5.3 Groundwater Charging Methods

Method		Outline
Well charge (injection)	Natural injection	An injection well is constructed above the subsurface head for permeation from the groundwater surface while using the head difference.
	Pressure injection	A pump is used to inject water by a head pressure greater than the static water pressure.
Surface charge (spreading)	Permeation pond	A permeation pond is constructed for permeation.
	Grooved drain	The surface is grooved to allow water to flow for permeation.
	Subsurface trench (underdrain)	A pipe with hole is laid several tens of centimeters deep under the ground to allow water to flow for permeation.
	Paddy field	Paddy fields are filled with water in the non-irrigated season for permeation.

The possible problems involved with artificial groundwater aquifer charging facilities are securing a construction plot and managing the facilities. To solve these problems, a simple dam may be constructed in a flood plain to store surface water in a wet year and allow it to permeate into the reservoir layer.

In artificial groundwater charge, fine particles contained in charge water often cause a major problem of blinding the permeation face by sedimentation. Bacterial propagation also causes blinding. Therefore, it is necessary to secure good-quality charge water and recover the permeation face periodically. A well can be cleared of fine particles by backwashing to prevent blinding. For a permeation pond, the permeation is covered with sand in advance and the sand is replaced periodically.

In Miyako District, a permeation pond is partitioned into two. Charge water is first led into one half for the sedimentation of fine particles and then into the other half for permeation into the ground.

The San jian bu subsurface dam in China is presently being planned as a subsurface dam of saltwater infiltration prevention. The dam length is 1,200 m, the maximum dam height is 23 m, and the gross reservoir capacity is 6,140,000 m^3. According to the plan, the impervious layer above the aquifer will be removed and the river water and rainwater will be permeated directly from the surface into the aquifer through artificial channels and wells to increase the groundwater charge. Four hydraulic auto flap gates are also planned to store surface water and charge groundwater. Of the four gates, the one furthest downstream also serves as a tide barrier. Table 5.5.4 shows the artificial groundwater aquifer charging facility plan for the San jian bu subsurface dam and Table 5.5.5 and Figure 5.5.2 give the general facility plan.

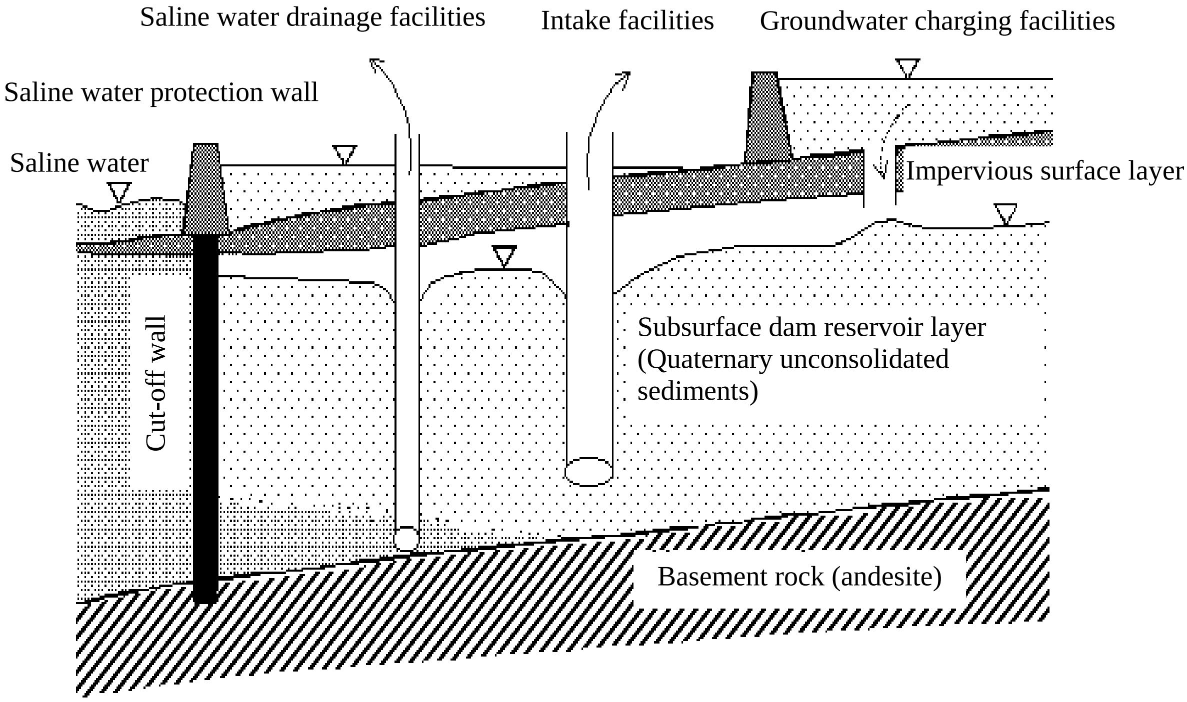
Table 5.5.4 Artificial Groundwater Aquifer Charging Facility Plan for the San Jian Bu Subsurface dam

Facilities	Outline
1. Charging channel	The charging channel is installed vertically at 1- to 20-m intervals on the riverbed of the main stream. The total number of channels is 300, the length is 50 to 100 m, the width is 2.0 m, and the depth is 1.5 to 2.0 m. To prevent blinding, gravel is backfilled as a filter layer. To tributaries of the river, 20 artificial channels 20 m in length, 2.0 m in width, and 2.0 to 3.5 m in depth are designed and backfilled by the grading of gravel.
2. Charging well	Charging wells are excavated at 10-m intervals along artificial channels to the main stream for 2,000 holes in total. The wells are 1.0 m in diameter and 2.0 to 3.5 m in depth and backfilled by the grading of gravel.
3. Flood control breakwater gate	The flood control breakwater gate is constructed above the subsurface dam as part of the dam. This gate consists of a surface dam and a hydraulic auto flap gate. The flood control section is 400 m in dam length and 2.0 m in mean dam height. The hydraulic auto flap gate is 100 m long and 1.5 m high with a reservoir capacity of 100,000 m^3.
4. Hydraulic auto flap gate	The hydraulic auto flap gate is installed at three upstream points. In design, the mean length is 75 m and the height is 1.2 m. The total reservoir capacity is 35,000 m^3.

Table 5.5.5 General Facility Plan for the San Jian Bu Subsurface dam

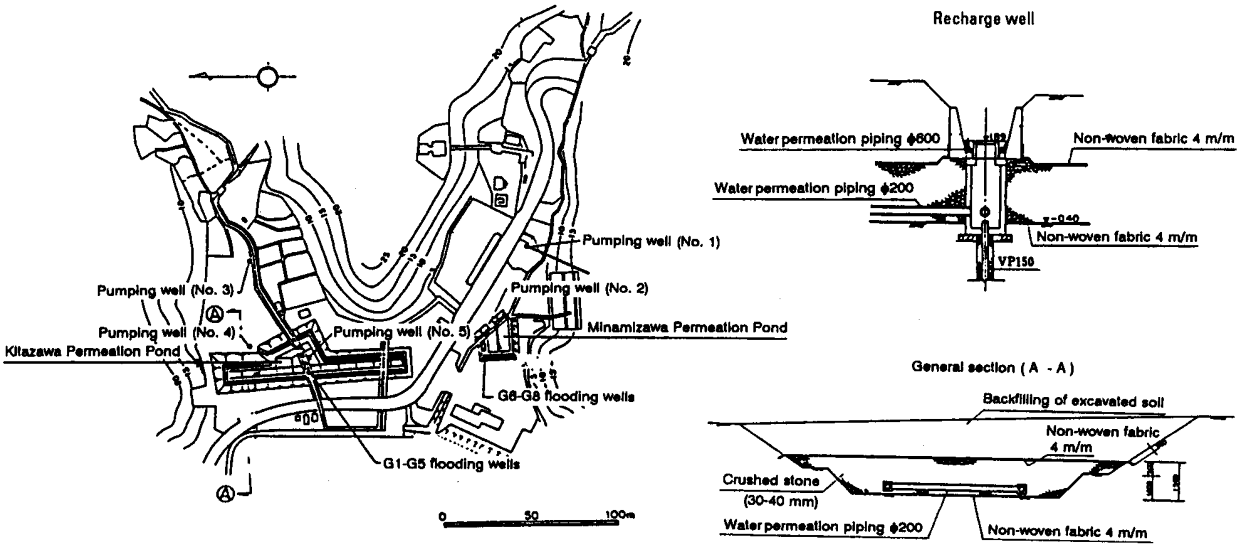
Item	Work volume	Contents
1. Subsurface cut-off wall	Extension: 1200 m Depth: 2.5 to 23 m	Constructed in the aquifer Grouting method Gravel layer
2. Ground cut-off wall	Saltwater infiltration prevention wall L = 400 m H = 2 m	Constructed on the ground of the dam axis to prevent the infiltration of saltwater
	Flood prevention wall: 3 L = 75 m H = 1.2 m	Constructed as part of the river bank to store fresh water at the upstream of the dam in case of a flood
3. Injection facilities (Artificial groundwater aquifer charging facilities)	Permeation groove: 300 L = 50 to 100 m B = 2 m D = 1.5 to 2 m	Two kinds of injection facilities constructed on the riverbed to charge the aquifer efficiently with surface water in the case of a flood
	Charging well: 2,000 wells φ = 1 m D = 2 to 3.5 m	
4. Collecting facilities	Underdrain: 4 φ = 1 m L = 400 m, Burial depth: 4.5 to 6 m	Pipes with hole laid at the upstream of the dam for intake from the aquifer
5. Pumping facilities	Collecting well, pump φ = 10 m	Intake wells constructed on both ends of a collection underdrain
6. Drainage facilities	Drainage facilities L = 15 km	Constructed to prevent contaminated water in the catchment area from permeating into the subsurface dam
7. Saltwater drainage facilities	Saltwater discharge well: 4 φ= 5 m D = 10 to 15 m	Wells constructed at the upstream of the dam to discharge saltwater
8. Monitor and management facilities	Observation well: 15 Control facilities: 1	Constructed to observe the water level and quality and to manage all facilities

Figure 5.5.2 Longitudinal Schematic Cross Section of the San Jian Bu Subsurface dam



The Tsunegami subsurface dam has gravel piles, two permeation ponds, and 18 charging wells in the reservoir area to promote groundwater charging. The permeation ponds have functions to collect surface water other than river water and lead them to charging wells and to permeate water into the ground. At the construction of a permeation pond, the surface is excavated and the layer up to about 2.3 m deep is replaced with crushed stones (grain size: 30 to 50 mm), and the crushed stones are covered with soil. The crushed stones are wrapped in non-woven cloth (thickness: 4 mm) to prevent the inflow of earth. The charging wells charge river water and water collected by the permeation ponds into the ground. Figure 5.5.3 shows the arrangement and structure of artificial groundwater aquifer charging facilities at the Tsunegami subsurface dam.

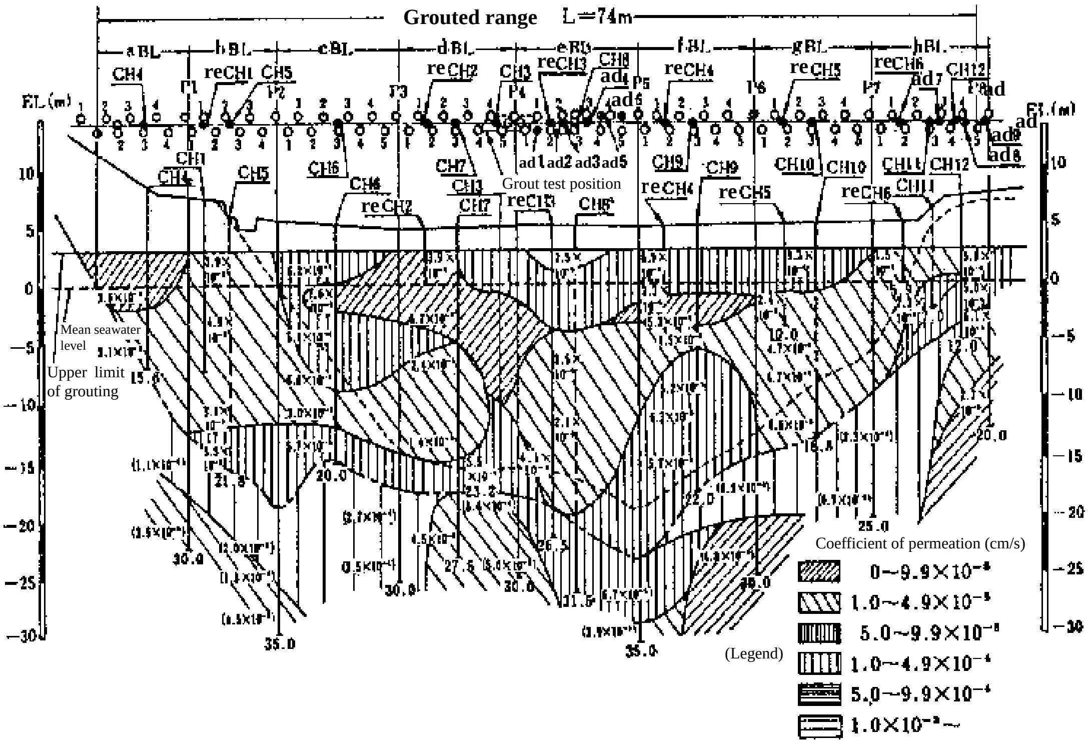
Figure 5.5.3 Artificial Groundwater Aquifer Charging Facilities at the Tsunegami Subsurface dam



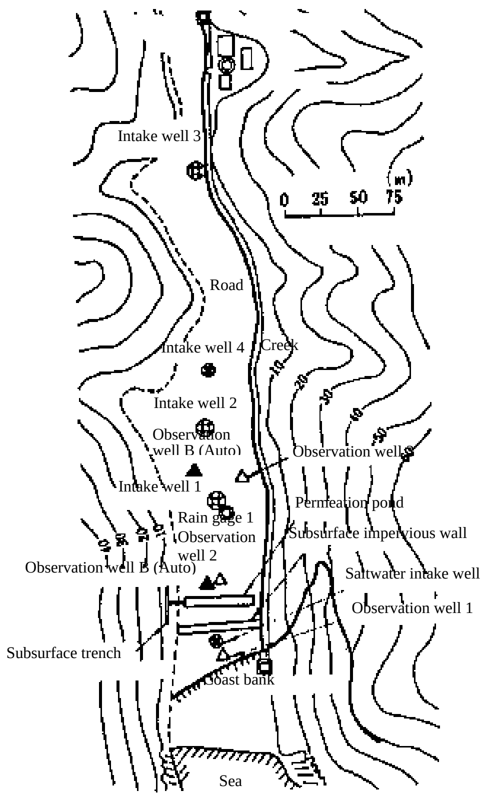
The Kabashima subsurface dam has a permeation pond and a subsurface trench (underdrain) in the reservoir area. These facilities store surface water temporarily to suppress dead runoff and promote groundwater charging. The subsurface trench buried on the right bank charged 250 mm in a wet season. Figure 5.5.4 shows the arrangement of facilities at the Kabashima subsurface dam.

Figure 5.5.4 Facilities at the Kabashima Subsurface dam

Permeation test results (after grouting)



Plane of subsurface dam facilities



Chapter 6 Execution of Construction Work

6.1 Construction Plan

6.1.1 Site and construction conditions

The laying down of a construction plan must be preceded by the investigation and identification of site and construction conditions. Site conditions refer to natural site conditions that may place restrictions on the execution of construction work, such as topography, geology, meteorology and groundwater related factors. Construction conditions, on the other hand, refer to social conditions that must be considered during the execution of construction work, including construction power supply, construction water supply, various regulations, and contact and coordination with related agencies. Through the processes of obtaining in-depth understanding of what constitutes the functional goals of subsurface dams and the applicable design concepts for them, and of examining the compatibility of these goals and concepts with site and construction conditions, it will become clear what should be considered during the execution of construction work.

6.1.2 Facility, machinery and procurement plans

Construction work must be preceded by the examination of the types, scale, performance and layout of required construction facilities and machines and the preparation of facility and machinery plans. When laying down facility and machinery plans, the following factors, among others, must be considered: design dimensions of various subsurface dam facilities, site and construction conditions, construction techniques, facility scale and construction processes.

Regarding machinery and materials used for construction, their procurement plan must be examined prior to the start of construction. The construction of the cut-off wall in subsurface dams in particular may use special excavators and materials. When planning to use such special equipment, prior information must be obtained regarding the locations and quantity of equipment available and it must be confirmed that the equipment is available during the construction period. In addition to that, when planning to use special materials, the material supply system must be checked to confirm the absence of supply system problems that may present obstacles to construction. When planning to use large machines or large volumes of materials, the transportation methods and routes must also be examined.

6.1.3 Process plans

Process plans for subsurface dam construction comprise a general process plan that reviews the order of the construction of facilities and a construction process plan that reviews the order of work to be carried out during the construction of each facility.

When developing a afflux subsurface dam, constructing the cut-off wall will increase the groundwater level in the reservoir area. With regard to the installation of intake facilities such as collecting wells,

vertical/horizontal collecting shafts and collecting trenches (underdrains), constructing these facilities prior to the cut-off wall and when the reservoir area groundwater level is low will ensure reduced underwater construction and improved economy and safety. There are also cases where constructing drainage facilities prior to the cut-off wall is more advantageous. On the other hand, the construction of tubular wells is not affected by the water level in the reservoir area. When developing a subsurface dam, constructing the cut-off wall may excessively increase the reservoir water level. It is, therefore, necessary to install drainage facilities prior to the construction of the cut-off wall.
As explained above, site conditions and the types, structures and workability of intake and drainage facilities must be reviewed. Then, in consideration of the timing of constructing these facilities against the timing of constructing the cut-off wall, an optimum general process plan must be laid down.

Workability (in terms of whether or not construction work can be executed) affected by meteorological conditions such as precipitation, wind power, air temperature and groundwater level fluctuations has a major impact on the construction process. It is, therefore, necessary when laying down a process plan to set up criteria to determine whether or not facility construction and work susceptible to meteorological and hydrological conditions can be carried out, and based on the meteorological data for at least the past 10 years, to estimate the number of workable days a year.

When planning to construct a subsurface dam in a location that is partially riverbed, precautions must be taken against increases in river water during flooding or the rainy period. Particularly when the open-cut method is used to construct the cut-off wall, water inflow to work sections may cause collapses and other damage to excavated ditches. It is, therefore, necessary, when planning to construct a small subsurface dam in a region with clear division between the rainy and dry periods, to schedule a process plan to start the construction of the cut-off wall at the end of the rainy period and complete the construction before the beginning of the next rainy period. If unable to escape from the effect of water inflow during construction, it will be necessary to use levees to protect work sections, or use temporary diversion facilities.

6.1.4 Establishment of control criteria

To ensure proper quality and workmanship control of each facility, control criteria must be established. The control criteria must be set within the range of possibilities in terms of construction technology. If unable to meet pre-designed values despite compliance to the control criteria, a review of the designed values or the volume of construction work must be considered based on the design purposes.

6.2 Execution of Construction Work and Construction Control

Construction work is executed in the following order: the acquisition and shaping of a construction site, construction of temporary structures, installation of construction facilities, execution of construction work and recovery of the original state. When construction work is being executed, process control, quality control, workmanship control and safety and health control must be performed.

6.2.1 Construction of the cut-off wall

To make sure that the cut-off wall of the subsurface dam can maintain water shielding performance as designed, attention must be directed to construction depth, wall thickness, wall hydraulic conductivity, cut-off wall continuity and penetration part during construction.

(1) Quality of the cut-off wall

To ensure wall quality, accurate understanding of site conditions is required. At the same time, construction work must be executed properly in accordance with the site conditions.

Wall quality is determined, for example, by the types and amounts of wall materials used, construction techniques and ground properties. The quality of walls made of cement solidifying materials is influenced by the mix proportions of wall materials, the amounts of wall materials charged, and the quality of construction water supply and groundwater. Particularly when constructing cut-off walls in locations with salinized groundwater, the types and mix proportions of wall materials must be determined in consideration of the influence of saltwater. Since the excavated ground itself becomes part of the wall materials when using the diaphragm wall of the deep mixing method, wall quality is significantly influenced by ground properties and how the ground was excavated and broken. Wall quality, as long as it meets the required standards of water shielding, strength and durability, need not be homogeneous. Nonetheless, homogeneous wall quality is preferable to ensure easy and accurate quality control.

To check the workmanship of the cut-off wall, the following methods are used.

(1) Inspection boring

Wall quality can be checked by boring into a completed wall, and then performing a laboratory permeability test and unconfined compression strength test, using core samples from boring. Moreover, a field permeability test must be performed using bored holes. However, since drifting may cause a deviation from the cut-off wall during excavation, care must be taken to improve the verticality of boring. One way to prevent drifting is to erect steel pipes or similar materials to a certain depth when the wall has not yet hardened, in order to use them as a guide during boring.

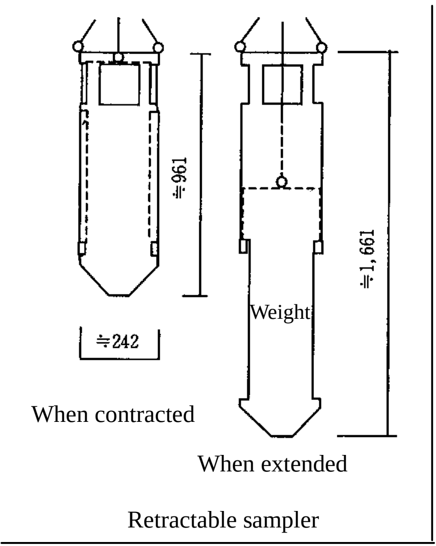
In the Nakajima subsurface dam, before the soil cement wall constructed by the diaphragm wall of the deep mixing method hardened, steel pipes, 50 mm in diameter, were inserted into the penetration part at 90-cm intervals along the dam axis. Using some of these steel pipes, holes 46 mm in diameter were bored to perform a field permeability test in order to measure the water permeability of the contact between the cut-off wall and basement using the packer method. Additionally, these bored holes can be used to monitor saltwater infiltration in weathered basement rocks, and if necessary, to perform grouting to improve the water shielding performance of the penetration part.

It must be noted, however, that if the use of the diaphragm wall of the deep mixing method, for example, has caused the entry of gravel into a wall, the gravel may cause jamming during boring, presenting a risk of partial destruction of the wall.

(2) Collection of wall materials and laboratory test

When using cement solidifying materials as wall materials, a part of the wall must be sampled from the specified depth using the sampling device shown in Figure 6.2.1 when the wall has not yet hardened. Next, the specimens, after they are produced from the sample, must be left standing to cure and harden. Then, a laboratory permeability test, unconfined compression strength test and other tests must be performed to check wall quality.

Figure 6.2.1 Sampling Device



(2) Maintenance of cut-off wall continuity

It is important, when constructing a cut-off wall in a dam, to maintain wall continuity in order to reduce water leakage from the wall. To this end, drifting (drifted ditches) must be reduced to a minimum during hole boring.

Certain excavators, such as the horizontal multi-axial operating excavator, can be position-controlled during excavation to correct drifting. On the other hand, when the diaphragm wall of the deep mixing method is used, for example, drifting cannot be corrected during excavation. If drifting occurs in this case, displacement increases as the hole gets deeper. When using an excavator like the horizontal multi-axial operating excavator, ensuring excellent construction accuracy in the initial stage of excavation will increase overall accuracy. The extent of drifting must be measured, and if using a position-controllable excavator, drifting must be corrected. If not using a position-controllable excavator, drifting must be measured and if the results indicate that the cut-off wall is discontinuous, excavation must be restarted.

In the Sunagawa subsurface dam, which used the diaphragm wall of the deep mixing method to construct the cut-off wall, the following measures were taken to improve excavation accuracy and reduce drifting:

(1) Used excavators with improved drilling torque, which have an adequate margin of excavation capacity.

(2) Improved the tip bit to make excavation easier and reduce the load during excavation.

(3) Established an optimum drilling speed that can keep drifting to a minimum and ensures no loss of economy. Set the initial drilling speed to 30 cm/min based on field test results, particularly in order to ensure accuracy in the initial stage of excavation.

(4) Laid concrete board on the work floor to stabilize and flatten the ground under the excavator, and improved the ground prior to excavation to reduce initial drifting.

(5) Checked the position and verticality of the excavator through location survey prior to excavation in order to ensure excavation perpendicular to the ground.

(6) Set up a guide wall and, at the same time, fixed the steel-framed guide ruler by welding in order to prevent deviation of the hole core. Removed the casing during pilot drilling and used it as a guide.

(7) Improved the stopper of the triaxial auger.

(8) Introduced the strictest possible construction control criteria since the accuracy of pilot drilling has a major impact on the accuracy of excavation that follows.

(9) Performed triaxial drilling in the following order: pilot drilling, pilot drilling and extraction in order to ensure the balance of load at the tip of the auger.

(10) Performed real-time measurement and analysis of how drifting is occurring and how the bit is being loaded during excavation, and gave instructions to excavator operators for improved operation.

(Measured drifting every 5 m drilled, and when drifting increased, pulled up the auger and restarted excavation. Repeated excavation to reduce the drilling load and thus prevent jamming when the electric current to the auger motor increased (as this means an increased drilling load.)

Excavators with slime removal function, for example, the bucket excavator, may be used to dig a new cut-off wall section that partly includes the already completed cut-off wall section. In this case, the materials for the adjacent wall section may be partially included in the slime. This is an indication that the continuity of the cut-off wall has been maintained.

(3) Construction of the penetration part

Since the penetration part receives maximum hydrostatic pressure and is susceptible to problems with cut-off wall quality, special precautions must be used during the construction of this part. The fact that the reservoir and basement often have different properties causes differences in excavation performance and in the workmanship of the cut-off wall in the penetration part.

In the Sunagawa subsurface dam, which used the diaphragm wall of the deep mixing method to construct the cut-off wall, the auger performance varied when drilling into the aquifer consisting of limestone and when drilling into the basement consisting of mudstone. More specifically, since limestone breaks into small fragments when drilled, it can be produced into a uniform soil cement. On the other hand, mudstone is hard to drill through and breaks into large fragments when drilled. Therefore, when drilling through mudstone in the penetration part, the tip of the excavator was repeatedly raised and lowered and an increased amount of grout, a solidifying material, was used. At the same time, precautions were used to ensure adequate blending to construct a uniform soil cement wall and to prevent water leakage from the contact between the cut-off wall and basement.

The construction depth is normally determined by adding the required length of the penetration part to the depth of the basement top. Depending on the basement properties (such as water permeability) in the penetration part, however, the length of the penetration part may change. It is usually difficult to obtain accurate prior information on the depth of the basement top and basement properties across the entire dam axis during the design stage. This makes it necessary, during the construction of the penetration part, to take these uncertain factors into consideration and ensure an adequate depth for the penetration part. It is, therefore, preferable to use an excavation method that allows, during excavation, immediate confirmation of the depth of the basement top and basement properties in the penetration part. If using a method that does not allow such confirmation, a construction depth must be calculated using the safety factor multiplier that matches the level of uncertainty.

When using excavation methods that involve the throwing of slime onto the ground surface, slime becomes an indicator of the basement conditions. However, when using the diaphragm wall of the deep mixing method, for example, it is not possible to immediately confirm whether or not the basement has been reached. Nonetheless, there may be cases where changes in the drilling load on the tip of the auger make it possible to assume that the basement has been reached.

(4) Steps of construction

When constructing a subsurface dam, the construction of the cut-off wall along the dam axis is highly flexible in terms of the order of construction; the construction can normally start from any section of the wall. However, it must be noted that with the progress of the construction of the cut-off wall, the groundwater level will increase in the reservoir area. This will accordingly increase the hydraulic gradient where construction has not started and may result in increased groundwater flow rates, presenting the risk of the wall material washing away.

In order not to allow increased groundwater flow rates where construction has not started, it is effective to start construction from where the basement is deep and gradually move to where the basement is shallower. The locations with large construction depth in particular are susceptible to reduced excavation accuracy, meaning that the locations are likely to become weak points in the cut-off wall. It is, therefore, preferable that construction be started early in the schedule in these locations. It is also recommended that construction be started early in the schedule in locations where hollow spaces and faults are assumed to be present.

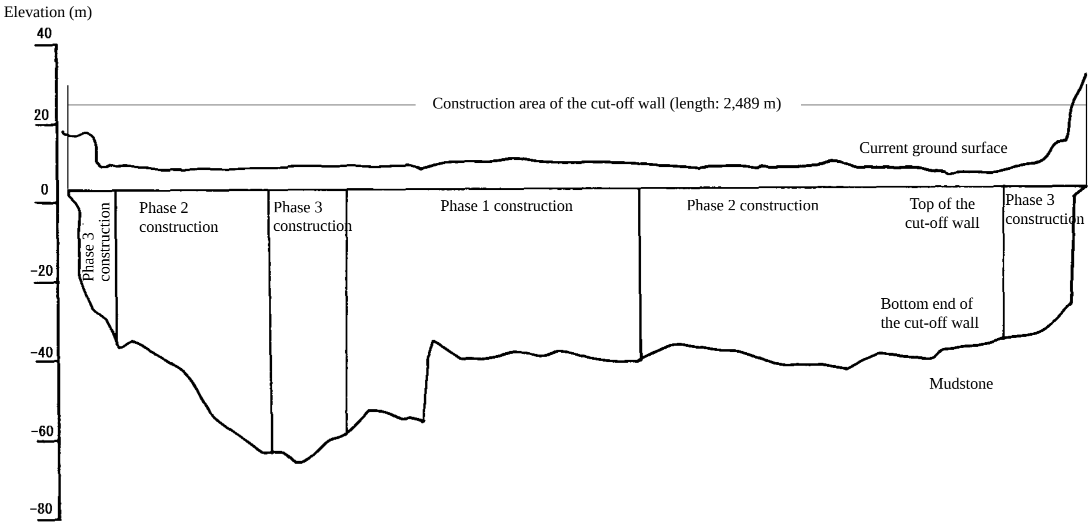
Closing a part of the dam axis earlier than the remaining part may change the groundwater flow direction and the hydraulic gradient, and thus force saltwater masses present in the reservoir area toward the lower reaches. An example of the Komesu subsurface dam, a saltwater infiltration prevention dam, is shown below.

In the Komesu subsurface dam, saltwater infiltration was already present on the reservoir side of the dam axis and the closing of the cut-off wall might have caused the infiltration of saltwater into the reservoir water. This made it necessary to schedule the order of construction of each cut-off wall section in a way to ensure the removal of a certain amount of saltwater in each stage of construction. The distribution and properties of residual saltwater masses in the reservoir area of the Komesu subsurface dam differed depending on their locations on the dam axis. More specifically, a small amount of residual saltwater was found in the center of the dam axis with a large amount of groundwater run-off, while saltwater was found infiltrating in a wedge shape deep landward along the subsurface valley on the left bank of the dam axis. A large amount of saltwater infiltration was also found on the right bank of the dam axis, with the area from around the groundwater table to the basement showing high salinity.

To remove these residual saltwater masses to a certain extent, the construction period of the watertight wall was divided into three phases and the extent of construction work to be done in each phase was determined (See Figure 6.2.2.).

(1) Phase 1 construction: Close the center of the dam axis with the least amount of saltwater infiltration in order to reduce the amount of saltwater infiltration to the reservoir area. The closing of this section causes groundwater from the upstream to flow toward both ends of the cutoff section, possibly pushing saltwater present there seaward.
(2) Phase 2 construction: Construct a part of the right and left banks of the dam axis. On the right bank of the dam axis, both ends were closed first to force saltwater out from the center and the center was closed last. The left bank of the dam axis was closed excluding the deep part of the subsurface valley where the basement is deep and saltwater infiltration is high. Delaying the construction of this subsurface valley section helps groundwater flows transferred from the newly cutoff sections to force saltwater out.
(3) Phase 3 construction: Close the deep part of the subsurface valley in the center of the left bank of the dam axis and both ends of the dam axis.

Figure 6.2.2 Profile of the Cut-off Wall of the Komesu Subsurface dam



The measurement of the electric conductivity of groundwater in the reservoir area before and after the construction of the cut-off wall confirmed lower electric conductivity and reduced distribution of saltwater in a wedge shape, meaning that the removal of saltwater is in progress to a certain extent. However, given the low hydraulic gradient of groundwater and the presence of locations with poor permeability, complete removal of saltwater in the reservoir area will not be possible if only using groundwater flows from the upstream to force saltwater out. Accordingly, after the installation of the cut-off wall, saltwater remaining in the reservoir area was removed from the well set up for salt-removing purposes.

(5) Other precautions regarding the construction of the cut-off wall

(a) Construction of the abutment

Slopes such as abutment slopes on both sides of a valley may not allow immediate installation of excavators. In this case, benchcuts must be performed to flatten the slope. This is an example where digging can reduce the subsurface construction depth, improve excavation accuracy and increase the economy of construction.

(b) Installation of the guide wall

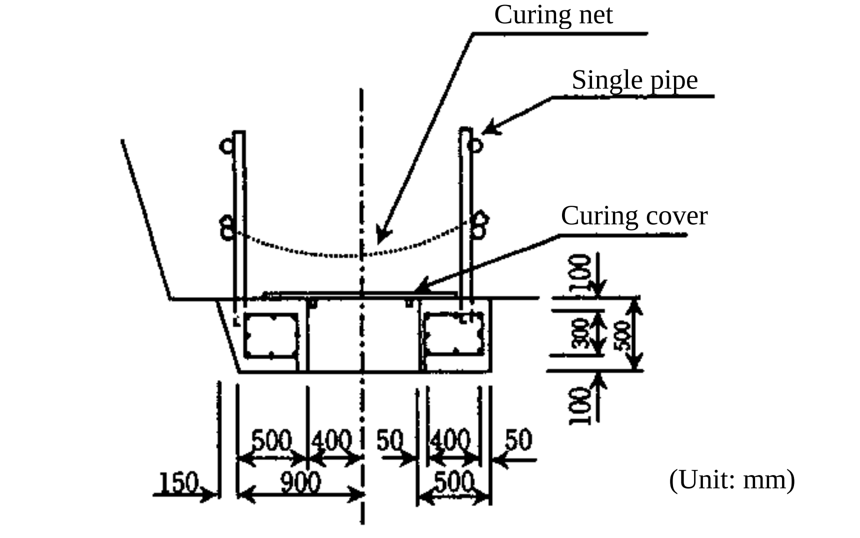
The excavation of unconsolidated layers near the surface layer may cause the collapse of ditch walls. Particularly when the groundwater level is low and the excavation above the groundwater table is deep, mud water, for example, makes the retention of ditch walls difficult, increasing susceptibility to collapse. Various measures are, therefore, undertaken to prevent such collapses including the installation of the guide wall and insertion of the metallic hole protective casing.

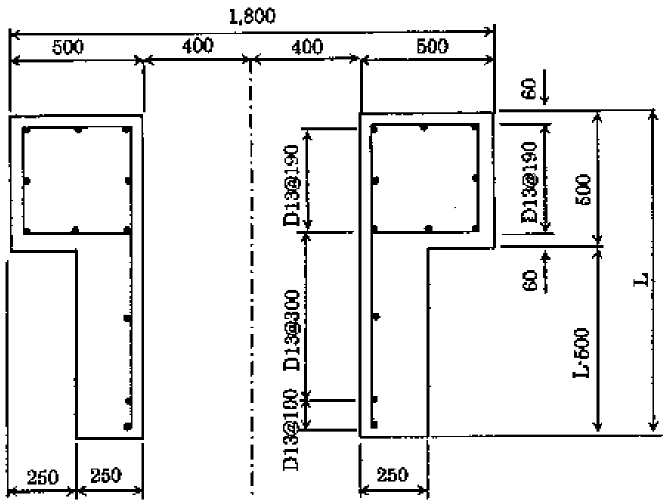
The installation of the guide wall helps determine excavating positions (the pile core position for pilot drilling and tunnel element core position for triaxial drilling). The guide wall can also be used as a reference for excavation accuracy, excavation depth, and horizontal and vertical measurement of the cut-off wall, in order to improve the excavation accuracy. Additionally, the guide wall can perform the following functions:

(1) Supports the load of equipment such as excavators and maintains the stability of the ground during construction.
(2) Prevents the dissipation of the stabilizing solution and maintains the stability of the surface of the solution.

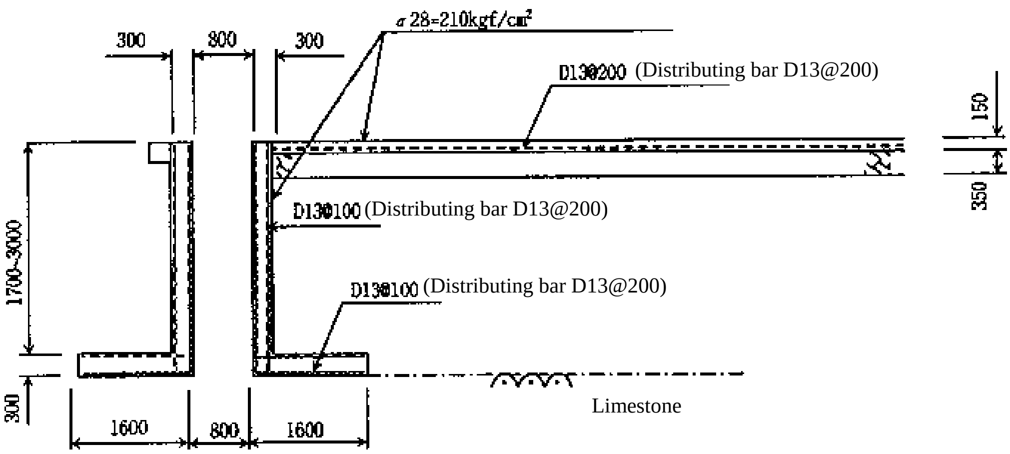
The guide wall dimensions must be determined in accordance with the soil type, ground conditions such as the groundwater level, the type and load of the equipment to be used, and surrounding conditions such as the presence of structures in close proximity. Figure 6.2.3 shows the structure of the guide wall set up in the Sunagawa subsurface dam.

Figure 6.2.3 Guide Wall in the Sunagawa Subsurface dam





Guide wall Type A



Guide wall Type C

(c) Effects on the surrounding ground and groundwater

When using mud water and liquid wall materials to construct the cut-off wall, measures must be taken to ensure freedom from contamination of the surrounding ground and groundwater as a result of leakage of these liquids. More specifically, a groundwater quality observation well must be set up in the downstream of the dam axis, to continuously observe groundwater quality by measuring, for example, pH and turbidity, for the purpose of monitoring the presence or absence, or the level of groundwater pollution, before, during and after construction. The measures that must be undertaken to prevent contamination include: to change the types, mix proportions and charging amounts of wall materials, to prevent contamination spread by controlling the groundwater level and to change the cut-off wall construction method.

(6) Special construction work

(a) Porous wall protection measures

To prevent the collapse of a porous wall (ditch wall) during excavation, installations such as the guide wall must be set up as explained above. However, if soils such as clay soils of low strength are present in the platform basement, the ground, despite the guide wall installed, will not be able to bear the load of the excavator and other equipment, and this may lead to the collapse of the porous wall.

When constructing the Sunagawa subsurface dam, for example, it was necessary to use a clay layer above the limestone as the platform basement and place machinery with a load of 120 tons. Three cast-in-place concrete piles, 700 mm in diameter, were driven into the clay layer at 1.5-m intervals until they reached the limestone, to transmit the load to the limestone and support the load of the machinery.

Apart from that, when a porous wall that had collapsed was likely to cause serious accidents such as the toppling of the excavator, the collapses were backfilled with sediment and triaxial drilling was performed from the ground surface. In this case, since a grout was used when backfilling the section equivalent to the overflow crest with sediment, the grout may impair the permeability of the section. This, therefore, made it necessary to keep the backfill section to a minimum.

(b) Measures to solve hollow space problems

When hollow spaces are assumed to be present, a cut-off wall construction method available depending on the scale of such spaces must be selected in the design stage. On the other hand, if hollow spaces are unexpectedly found during construction, their location and scale must be immediately identified to examine applicable measures. Potentially applicable measures include changing the construction method, changing installation materials and filling the hollow spaces.

When the Fukusato subsurface dam was being constructed, it was detected from the lowered grout surface during drilling that hollow spaces (a stalactite cave) were present in the cutoff section. The first hollow space was located around a depth of 19 to 20 m, at a size of about 2 m high × 5 m wide × 3.5 m deep and with a capacity of approximately 35 m^3, and from there another hollow space, 30 cm in diameter, was found further down. To solve this problem, 51 m^3 of soil removed from excavation was charged, followed by additional charging of 16 m^3 of sand and water. Then, triaxial drilling was performed using hardening grout (liquid II). After these measures, the liquid surface was calm, presumably indicating that the hollow spaces were filled. Following this, inspection boring was performed in order to sample cores from what used to be hollow spaces and to check that a wall had been formed. At the same time, a field permeability test as well as an unconfined compression strength test for wall specimens were performed to confirm that control criteria were met.

(c) Construction within the tunnel

For example, when the uncut-off area along the dam axis between the top of the cut-off wall and the ground surface is very large or when the ground surface cannot be used for construction, the cut-off wall must be constructed from within a tunnel.

When it became difficult, from the perspective of protecting the environment including the ecosystem, to construct the cut-off wall from the ground surface while the Kikai subsurface dam was being constructed, the cut-off wall was constructed from within a tunnel in part of the dam axis. A tunnel with an inner section approximately 6 m high was set up, from which to carry out the diaphragm wall of the deep mixing method using a small excavator.

(7) Examples of construction using various methods

(a) Cast-in-place pile type in-site churning method

1) Steps of construction

The Sunagawa subsurface dam used the cast-in-place pile type (triaxial) in-site churning method for construction of the cut-off wall. The steps of construction are detailed below (Figure 6.2.4).

(1) Temporary construction

Constructed a plant, stockyard, work floor and guide wall.

(2) Casing and drilling

Inserted an auger, 600 mm in diameter, into a casing, 710 mm in diameter, and drilled down to 20 m at 90-cm intervals and removed soil in order to ensure the permeability of the overflow crest and prevent drifting during pilot drilling, the next process.

(3) Pilot drilling

Used the casing as a guide and drilled further down below the 20 m point to a required depth using an auger, 600 mm in diameter, and non-hardening grout (liquid I), in order to reduce the load on the auger and prevent drifting, prior to the construction of the continuous wall by triaxial drilling.

(4) Leveling of the overflow crest

For leveling purposes, removed the ground cover remaining between holes that were cased and drilled down to 20 m using the triaxial auger, 550 mm in diameter, after pilot drilling, in order to dig trenches over the overflow crest. Removed sediment using the rod-type clamshell excavator. This process enabled the removal of soil that would rise during the next process – triaxial drilling – and surplus grout using the rod-type clamshell excavator, the prevention of grout infiltration toward the overflow crest and the maintenance of permeability of the overflow crest.

(5) Triaxial drilling

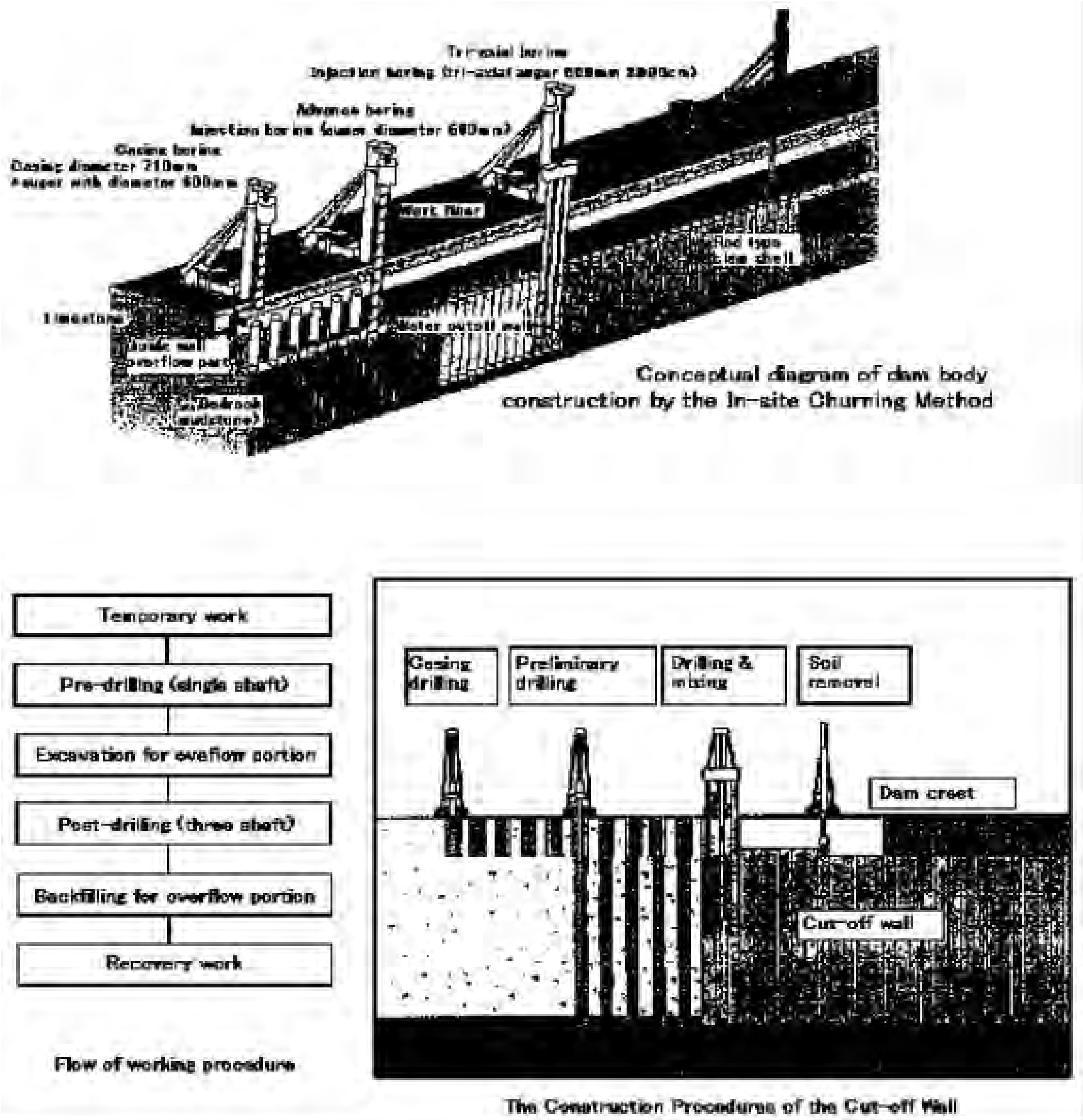
Excavated the section that had been untouched during pilot drilling down to a required depth using the triaxial auger, 550 mm in diameter. Used grout (liquid I) during excavation in order to cool the front bit of the auger, reduce the drilling load and prevent water leakage. When triaxial drilling reached a required depth, changed over from grout (liquid I) to hardening grout (liquid II), raised the triaxial auger while pouring grout from the tip of the auger, and blended the fractured limestone with liquid II.

Mudstone that formed the basement was likely to adhere to the auger similar to clay when drilled, reduce the uniformity of soil cement, and reduce the quality of the wall. Therefore, when triaxial drilling reached the bottom, the auger was raised and lowered twice along the deepest 5-m section for sufficient blending. At the same time, used grout 2 to 2.5 times more than normal per 1 m to increase wall quality.

(6) Adjustment pile

During triaxial drilling, one of the three holes drilled during the preceding drilling operation was drilled again. However, with the progress of drilling, drifting occurred and the deviation from the previously drilled hole increased. Therefore, when an interruption to the continuity of triaxial drilling was detected through measurement by the insertion inclinometer, work (adjustment pile) was performed in addition to triaxial drilling.

Figure 6.2.4 Conceptual Diagram of Cut-off Wall Construction Using the Diaphragm Wall of the Deep Mixing Method



2) Maintenance of the function of the overflow crest

This method used the following techniques in order to maintain the permeability of the overflow crest.

(1) Cased and drilled a hole down to 20 m during monoaxial drilling while ensuring no infiltration of grout into the surrounding soil (possible up to a depth of approximately 25 m).

(2) Discharged surplus grout using the rod-type clamshell excavator while triaxial drilling was performed to drill holes, in order to prevent the grout surface from rising to the level of the overflow crest during drilling.

However, to ensure the permeability of the overflow crest when the depth down to the top of the cut-off wall exceeds 25 m, digging is required until the difference in elevation between the work floor and the top of the cut-off wall is reduced to 25 m or less to set up a work floor.

3) Quality control of the cut-off wall

In the Sunagawa subsurface dam, specimens were collected from a depth of 25 m below the platform basement using a retractable sampler. The specimens were then membrane-cured for permeability testing and measured by the permeability tester for hydraulic conductivity two and four weeks later. For compression testing, specimens were cured in a specimen mold for concrete compression test (100 mm in diameter × 200 mm high) and underwent an unconfined compression strength test two and four weeks later.

Additionally, core boring from the top of the cut-off wall to the basement was performed to collect wall specimens. The boring was performed when the wall aged past 28 days. An unconfined compression strength test was performed using the collected specimens. Furthermore, using the bored hole, a field permeability test using the single packer method was performed to check the permeability of the wall.

4) Maintenance of construction accuracy

For the Sunagawa subsurface dam, the following control criteria were established for the diaphragm wall of the deep mixing method:

Precision of casing and drilling (drifting): Within 0.5% of the excavation depth as a control target

Precision of pilot drilling (drifting): Within 1.0% of the excavation depth as a control target

Precision of triaxial drilling: The continuity of tunnel elements must be maintained.

In order to determine the state of excavation, real-time operations were performed: to determine the hardness of the soil and the presence or absence of hollow spaces using a computerized system, to measure drifting, and to control the amount of grouting and workmanship. As for drifting, a fixed inclinometer was placed inside the tip of the auger rod for pilot drilling and the center auger rod for triaxial drilling, rod rotation was stopped every 5 m drilled and inclination was measured. Moreover, during triaxial drilling, after excavation reached the planned depth, the rod was separated, an inclinometer was manually inserted into each of the rods on both ends, the vertical deviation was measured every 2 m drilled, and the shape of final drifting was determined by accumulating the data.

The measured data was transferred to a personal computer to examine intrinsic errors and measured data and calculate the amount of drifting and interaxial distance, and the results were output to the display or printer. The data was output in the form of a workmanship plan and projected cross section of the dam axis in order to detect locations causing discontinuity of the cut-off wall during triaxial drilling.

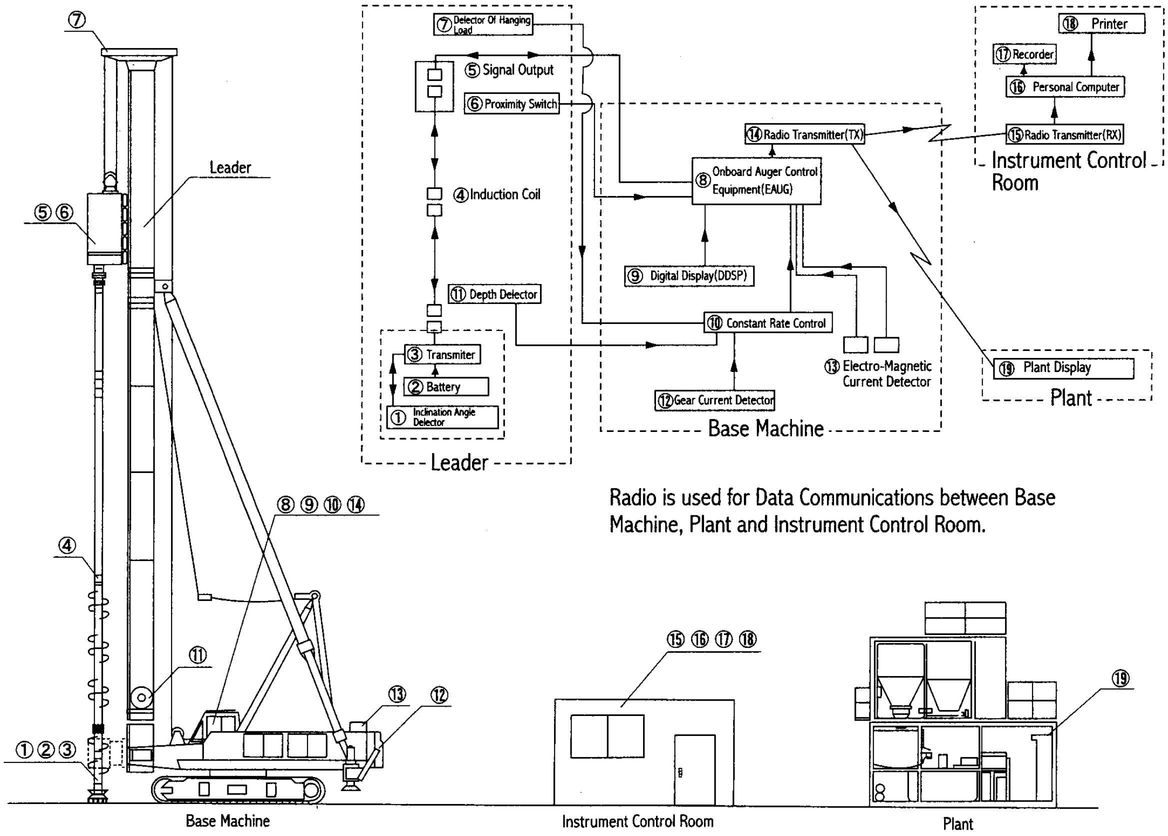
General information on control items when using the diaphragm wall of the deep mixing method are shown in Table 6.2.1 and Figure 6.2.5.

Table 6.2.1 Control of the Diaphragm Wall of the Deep Mixing Method in the Sunagawa Subsurface dam

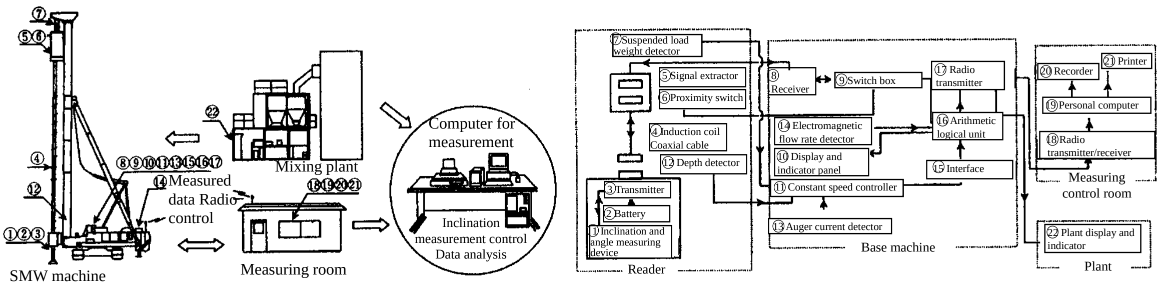
Control Item		Measuring and Control Method
Grout mixing		Measurement of each component material
Verticality during casing and drilling		Collimation in both X and Y directions in a transit
Measurement during excavation	Construction depth	Measurement of the wound wire length by a rotary encoder fitted to the base machine
	Inclination angle of the auger	Placement of a fixed inclinometer inside the rod at the tip of the auger
	Amount of grouting	Installation of an electromagnetic flow meter in the base machine
	Electric current to the auger motor	Measurement of the electric current by an ammeter to determine the drilling load
Grout surface position		Measurement of the grout surface position immediately after and one and two days after pilot drilling Use of control to maintain the grout surface level in the drilled hole below the level of the overflow crest during triaxial drilling
Final drifting shape (workmanship)		Insertion of an inclinometer into the triaxial auger after excavation
Finish on the dam crest top		Pouring of concrete up to the dam crest elevation
Cut-off wall quality		Unconfined compression strength and laboratory permeability testing of collected and cured specimens Inspection boring (Unconfined compression strength and field permeability testing of cores)

Incidentally, when using the diaphragm wall of the deep mixing method, it is difficult to accurately determine the depth of the basement reached during excavation. The depth of the top of the basement rock is, therefore, measured every 20 m drilled along the dam axis. In some cases, changes in the drilling load (changes in the value of the electric current to the auger motor) may become an indication that the bedrock has been reached. Depending on the type of soil in the ground excavated, the vibration during excavation or excavation noise varies because different soils have different properties. Measuring and analyzing the vibration or sound may allow real-time confirmation of whether or not the bedrock has been reached.

Figure 6.2.5 Conceptual Diagram of the Construction Control System in the Sunagawa Subsurface dam



● Concept Chart of Construction Management System



Concept Chart of Construction Management System

(b) Bucket excavation method

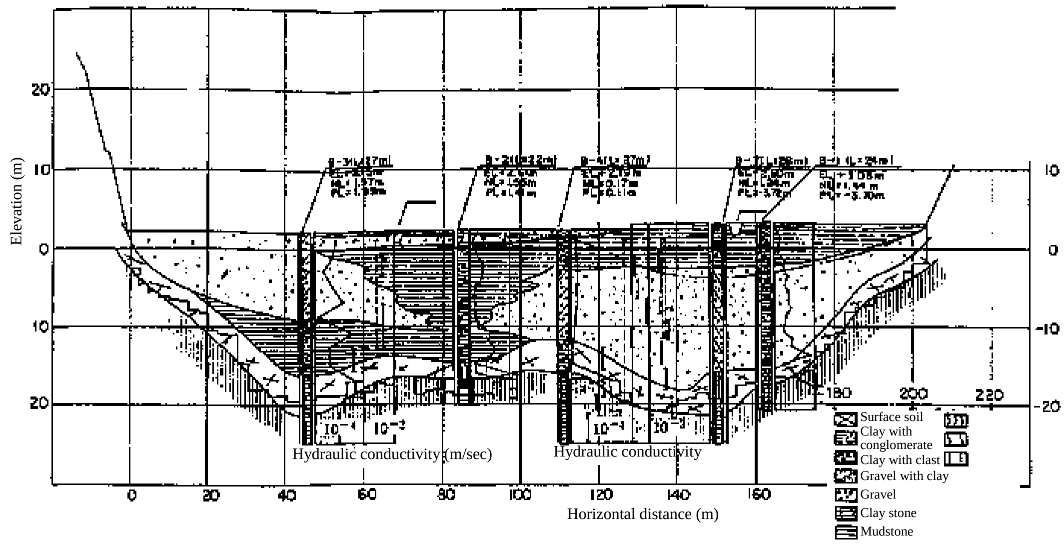
The Tsunegami District in Fukui Prefecture faced increasing problems with the use of groundwater. These problems, associated with saltwater infiltration, resulted from groundwater level declines caused by increased pumping. This circumstance necessitated the construction of the Tsunegami subsurface dam, a saltwater infiltration prevention dam, in its coastal area.

The basement of this district consists of Paleozoic sedimentary rocks, and is between 16 and 20 m deep on the plain area. The aquifer consists of clay and gravel layers with pebbles. Through a pumping test, the hydraulic conductivity was determined to be between 10^{-2} and 10^{-4} cm/S. The effective porosity of the aquifer was also estimated to be 0.15 to 0.2.

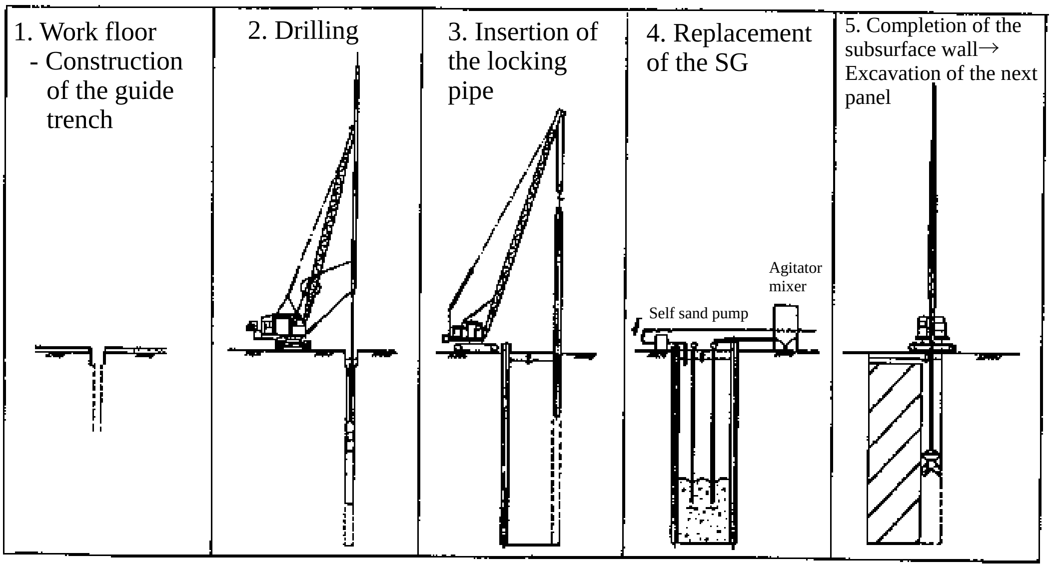
The cut-off wall was constructed by excavating a continuous subsurface wall ditch and using the self-hardening slurry replacement method. The excavation of the continuous subsurface ditch used a kelly 40M bucket excavator with a kelly-bar attachment. Mud water was used to maintain the stability of the porous wall. After excavation, mud water was replaced by self-hardening slurry using a tremie pipe. Self-hardening slurry is made of blast furnace cement, bentonite and potassium sulfate, and when hardened, forms a highly impermeable wall. To enable a permeability test and grouting of the weathered rock layer with many fissures in the penetration part, steel pipes were inserted down to the bottom of excavation at 1-m intervals in the wall center before the self-hardening slurry hardened. Figure 6.2.6 shows a sectional view of the Tsunegami subsurface dam.

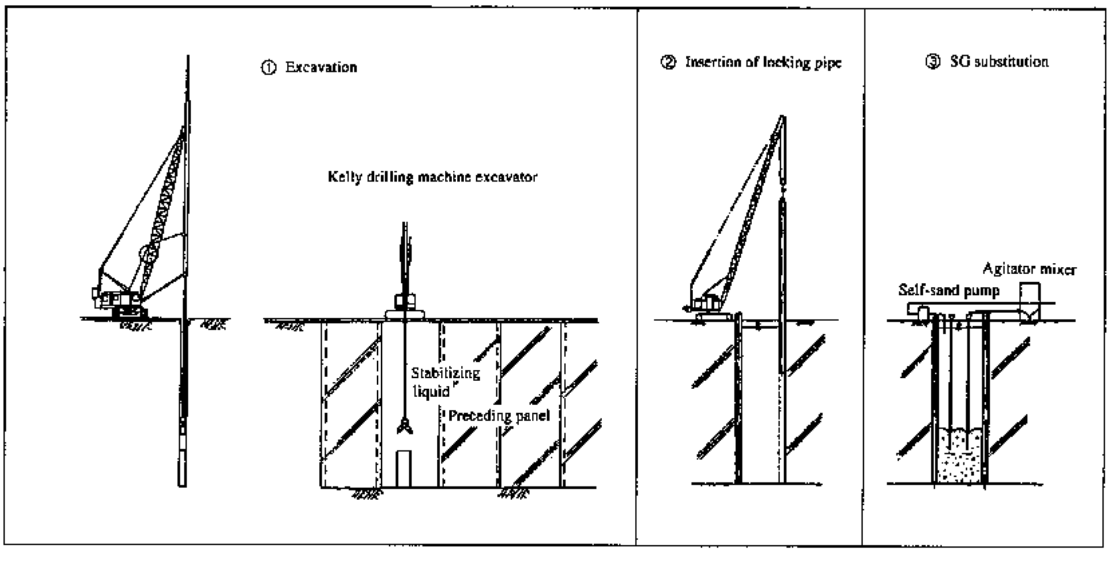
The increased groundwater level within the reservoir area and the overflow that occurred over the crest of the dam after the construction of the cut-off wall proved the effectiveness of the cut-off wall. The salinity of groundwater, which was previously 1,500 mg/lit, gradually decreased to about 300 mg/lit following the completion of the cut-off wall. Nonetheless, a tendency toward increased salinity was observed when water demand increased in summer. This phenomenon was presumably caused by the entry of saltwater, which had infiltrated the aquifer and remained in its bottom before the subsurface dam was constructed, during increased pumping in summer.

Figure 6.2.6 Overview of the Construction of the Tsunegami Subsurface dam



Cross Section (Cut-off wall location)



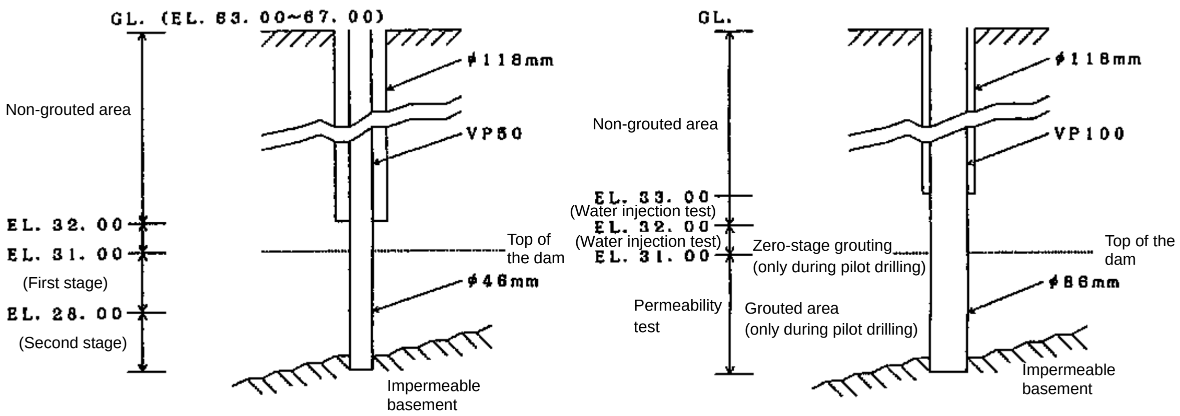


Construction sequence diagram

(c) Grouting

As previously explained, when constructing the cut-off wall in the Sunagawa subsurface dam, the diaphragm wall of the deep mixing method was applied to a large part of the wall, and the stage grouting method was also partially used to improve cost effectiveness. The overflow crest was drilled using the rotary percussion boring method (118 mm in diameter), while the grouting section (cut-off wall section) was drilled using the rotary boring method (core collection 86 mm in diameter and grouting alone 46 mm in diameter). Stage grouting was performed by repeating the excavation and grouting processes. In the Sunagawa subsurface dam, to prevent grout from rising to the level of the overflow crest, cap grouting (zero stage, EL. 31 m) was performed first. Then, grouting was performed in two stages: the first grouting stage (EL. 31 to 28 m) and the second grouting stage (below EL. 28 m) (Figure 6.2.7).

Figure 6.2.7 Conceptual Diagram of Grouting



(Grouting hole) (Pilot and check holes)

The steps of grouting performed in the Sunagawa subsurface dam are shown in Table 6.2.2. Grouting is performed in the following order: temporary construction, pilot drilling, rough grouting, finish grouting and checking. Construction control performed at the same time includes drifting measurement, water injection test, water test, permeability test and core collection.

Table 6.2.2 Steps of Grouting Performed in the Sunagawa Subsurface dam

Work Process	Work Detail
Temporary construction	(1) Installation of plant, water supply and electrical facilities (2) Casting of the work floor (base concrete)
Pilot drilling	(1) Boring of the overflow crest down to EL. 33 m (100 mm in diameter) (2) Erection of the guide pipe (VP100 mm) (3) Measurement of drifting (4) Boring of section at EL. 33 to 32 m (86 mm in diameter, core collection and water injection test) (5) Boring of section at EL. 32 to 31 m (86 mm in diameter, core collection and water injection test) (6) Zero-stage grouting (Cap grouting) (7) Boring of section below EL. 31 m (86 mm in diameter, core collection and permeability test) (8) First-stage grouting (Second-stage grouting is performed by carrying out (7) and (8) again.)
Rough grouting	(1) Boring of the overflow crest down to EL. 32 m (100 mm in diameter) (2) Erection of the guide pipe (VP50 mm) (3) Boring of section at EL. 32 to 31 m (46 mm in diameter) (4) Zero-stage grouting (Cap grouting) (5) Boring of section below EL. 31 m (46 mm in diameter, water test) (6) First-stage grouting (Second-stage grouting is performed by carrying out (5) and (6) again.)
Finish grouting	The same construction techniques are used as for rough grouting.
Checking	(1) Boring of the overflow crest down to EL. 33 m (100 mm in diameter) (2) Erection of the guide pipe (VP100 mm) (3) Measurement of drifting (4) Boring of section at EL. 33 to 32 m (86 mm in diameter, core collection and water injection test) (5) Boring of section at EL. 32 to 31 m (86 mm in diameter, core collection and water injection test) (6) Boring of section below EL. 31 m (86 mm in diameter, core collection and permeability test) The second stage is performed by carrying out (6) again.

Construction control when using the grouting method includes measurement of the hydraulic conductivity of the ground in the pilot hole prior to grouting. Moreover, to check the workmanship and quality of the cut-off wall after the completion of grouting, inspection boring was performed to carry out permeability testing. The control criteria for grouting performed in the Sunagawa subsurface dam are shown in Table 6.2.3.

Table 6.2.3 Control Criteria for Grouting Performed in the Sunagawa Subsurface dam

Work Type	Item	Control Criteria	Frequency of Measurement and Other
Pilot drilling	Deviation of the center line Interval between holes Depth Drifting	±30 mm ±50 mm –50 +100 mm ±1% (Target)	All holes All holes All holes All holes
Rough grouting Finish grouting Checking	Deviation of the center line Interval between holes Depth Drifting	±30 mm ±50 mm –50 +100 mm ±1% (Target)	All holes All holes All holes Check holes
Water injection test Permeability test	Grouting pressure	±10% of specified pressure	Check holes Pilot holes
Grouting	Grouting pressure Grouting amount Measurement of component materials	±5% of specified pressure including machine errors ±10% when permeability is excellent ±1% of the unit amount of grouting Water ±1% Cement ±1% Admixture ±2%	All grouting holes Entire amount of grouting All grouting holes and every time cement milk is produced

6.2.2 Construction of intake facilities

(1) Preliminary survey of installation locations of intake facilities

Aquifers often have heterogeneous properties, and depending on the location, the basement depth (aquifer thickness), permeability and other water intake properties may vary widely. It is important to select optimum locations to install intake facilities. With regard to the selection of intake facility locations, therefore, the entire reservoir area must be surveyed to determine aquifer properties, and then, water intake analysis must be performed to determine the locations of intake facilities, as previously described in 5.3 Designing Intake Facilities. However, it is difficult to accurately determine the properties of each water intake point in the design stage. This fact necessitates an extensive preliminary survey before the start of construction in order to check reservoir properties at each water intake point. Ideally, the survey would include pilot boring at scheduled intake locations to observe strata and measure the basement depth as well as bore hole logging and a simple pumping test to determine the hydraulic conductivity of the reservoir and the potential amount of water intake. If the properties of the scheduled intake locations show considerable deviation from design conditions, the alteration of the intake facility design or change of the intake locations must be considered.

(2) Timing of construction

Depending on the type of intake facility, the timing of construction must be determined in consideration of the groundwater level and other factors. As explained in 6.1.3 Construction Plan, it is preferable that the collecting well and horizontal collecting shaft, for example, be constructed before the groundwater level starts to rise following the construction of the cut-off wall. It may also be necessary in regions with seasonal changes in the groundwater level to schedule the construction plan so as to start construction before the groundwater level starts to fall and to complete construction before the groundwater level starts to rise again.

As will be explained later, it is also preferable to perform a water intake test to determine the performance of intake facilities before the groundwater level starts to rise following the construction of the cut-off wall.

Tubular wells can be constructed at any time regardless of the rising and falling of the groundwater level. However, a proper excavation method must be selected in consideration of the need to remove slime and the method for retaining the porous wall. When planning to manually carry out excavation work, for example, in a large diameter well, excavation must be carried out when the groundwater level is low, and at the same time, sand pumps and other necessary equipment must be available for draining.

(3) Precautions during construction

Prior to the start of construction, water sources, surplus soil yards, construction yards, construction roads and other facilities must be in place and available. In full consideration of site and construction conditions, construction machines and equipment must have the required capacity and size.

When constructing intake facilities, safety must be ensured, for example, by preventing the collapse of the porous wall during excavation, and at the same time, care must be used to minimize the deterioration of permeable properties of the reservoir around the construction area. Special attention must be directed toward the removal of mud cake and slime. Fresh water drilling is ideally applied to the construction of tubular wells to prevent the deterioration of permeability of the porous wall. Attention must also be directed to assuring freedom from clogging during excavation, and if concern rises over the collapse of the porous wall, certain measures must be used, including the insertion of casing to protect the porous wall.

(4) Pumping test

All parameters used for designing intake facilities include uncertainties. Heterogeneous reservoir properties also often cause location-specific variations in water intake conditions such as hydraulic conductivity. Accordingly, these facts make it absolutely necessary to perform a pumping test to determine the relationship between the amount of water intake and the amount of lowering of the groundwater level for the purpose of ascertaining the possible intake capacity following the installation of intake facilities. It is particularly important for intake facilities to allow the pumping of required amounts of water at the minimum reservoir level. It is therefore necessary to perform a pumping test when the reservoir water level is closest to the minimum, to determine the possible intake capacity at the minimum reservoir level. If the reservoir water level during a water intake test is higher than the minimum, whether or not required amounts of water intake can be made available at the minimum reservoir level must be examined carefully.

Pumping testing in tubular wells comprises a preliminary pumping test, stage pumping test and continuous pumping test. The preliminary pumping test is designed to perform cleaning using pumped water and roughly determine pump discharge and pump performance. The stage pumping test is performed to determine pump discharge. During the stage pumping test, pump discharge is changed in stages to determine the relationship between pump discharge and the amount of lowering of the water level, in order to estimate the well capacity, namely the possible amount of pumping. The continuous pumping test, which involves constant volume pumping during a specified time period, is designed to record the amounts of lowering of the water level and the amounts of recovery of the water level after pumping stops. The Theis' method, Jacob's method, recovery method and other relevant methods are used to analyze the test results to determine the hydraulic conductivity, storage coefficient and influence area of the aquifer.

(5) Construction of tubular wells

Tubular wells are normally constructed in the following order:

(1) Temporary construction and transport and assembly of excavators

(2) Drilling

Excavation methods generally used for tubular wells include the rotary method and percussion method, as shown in Table 6.2.4. It is essential to carry out construction while making sure not to allow slime or mud water to deteriorate the permeability of the porous wall.

Table 6.2.4 Excavation Methods for Tubular Wells

Method	Rotary Method	Percussion Method	Air Hammer Boring Method
General information	Drilling by using the rotary core tube or bit in the excavator. The porous wall is protected by mud water.	Drilling by using the free fall of a bit suspended from a wire that provides a breaking impact on the stratum. The porous wall is protected by mud water.	Drilling by using a bit and percussion drill (air hammer) Placed in the bottom of the hole to provide a breaking impact on the stratum. The pressure of the compressed air and the hammer weight provide impact force to the bit.
Applicable diameters	40 to 500 mm	150 to 600 mm	150 to 600 mm
Slime removal method	Removed with excavation water (fresh water or mud water)	Removed using a hammer grab or baler	Removed by compressed air

(3) Electric logging

Electric logging must be performed in order to check aquifer properties.

(4) Insertion of casing

(5) Filling of the filter

Ballasts of appropriate size must be used to fill the strainer as filter material. With regard to the gap between the casing in the top of the filter and the porous wall, clay or concrete must be filled to prevent surface water inflow.

(6) Hole cleaning (swabbing and other)

Swabbing (surging) is a type of cleaning method used to remove slime and mud cake in the porous wall. More specifically, a surge plunger such as the baler is inserted into the casing and is repeatedly raised and lowered. Also available is the jetting method, which uses a jet nozzle to feed high-pressure water, air or steam to the strainer for cleaning. Concurrently, the pumping and discharging of mud must be carried out using, for example, a sand pump.

(7) Disassembly and removal of excavators

(8) Installation and piping of the pump for pumping test

To prevent groundwater pumped during the pumping test from infiltrating again to the subsurface in the proximity of the well, the water must be properly drained.

(9) Pumping test

(10) Removal of machines and equipment

In the Sunagawa and the Fukusato subsurface dams, water intake analysis was performed to determine the locations of tubular wells. The intake capacity of each well, however, varies depending on the basement depth at each well location and local water intake properties. Prior to the construction of a well, therefore, a hole was bored immediately near the well location in order to determine the basement depth. Moreover, if no pumping test had been performed in the proximity of the well, a hole was bored with a 118-mm diameter and used to perform a simple pumping test. After the water intake properties were determined based on the survey results, the well was drilled.

The swabbing method was used to clean the well hole. By performing a pumping test using the previously-mentioned bored hole as the observation well, the water intake properties of each well were determined.

6.2.3 Construction of drainage facilities

To allow the overflow of excess reservoir water from the top of the crest of the cut-off wall, it is important not to allow the deterioration of the permeability of the ground surrounding the overflow crest during the construction of the cut-off wall. To accomplish this end, slime and grout must be properly removed during excavation to ensure freedom from problems such as clogging of the overflow crest, and at the same time, construction control must be properly performed to allow no infiltration of mud water or cut-off wall materials into the ground surrounding the overflow crest. Additionally, to ensure the required permeability of the overflow crest after the construction of the cut-off wall, the overflow crest must be backfilled with highly permeable materials such as crushed stones.

When constructing drainage facilities such as underdrains, care must also be used not to allow the deterioration of the permeability of the ground in contact with drainage facilities. When planning to install underdrains for use as drainage facilities, they must be constructed through the following procedures.

(1) Determination of the route of underdrains, and confirmation of the drainage port, upstream reference point and underdrain connection points
(2) Transport and placement of materials
(3) Excavation of the underdrain
(4) Laying of water supply pipes
(5) Charging of filter materials
(6) Construction of the drainage port
(7) Backfilling and topsoil improvement

Underdrains are ideally constructed when the rainfall and groundwater level are both low and thus soil is dry. Since groundwater may flow into the ditches during the construction of underdrains, construction must start with the drainage port, and progress from the downstream to the upstream end. The laying of pipes and charging of filter materials must be done quickly to prevent the accumulation of sediment due to the collapse of the ditches. During the construction of underdrains, supervision must be introduced to control the following specifications: construction lengths and intervals, angles for laying underdrain pipes, excavation depths, and embedding depths of water supply pipes and filter materials, in order to ensure drainage performance as designed.

Once the construction of underdrains is completed, how they are embedded in the ground cannot be viewed from the surface. So, if a drainage problem occurs even partly in the network of these underdrains, the drainage effect of the underdrains is reduced. When constructing underdrains, therefore, construction control must be thoroughly monitored. At the same time, how the construction is being done must be recorded to later enable the confirmation of whether or not the construction was carried out as designed. Additionally, with regard to the locations of embedded underdrains, it must be ensured that these locations can be identified on site and on drawings, to enable the protection, maintenance and management of these facilities.

When constructing underdrains, it is important to ensure proper angles for laying underdrain pipes (intake pipe and collecting pipe). The bottom of the ditches for underdrains must therefore be shaped carefully in order to ensure uniform angles. The degree of perfection of the filter material charging process also has a significant impact on the function and durability of underdrains. The filter materials must be charged up to the designed height and to the specified density.

6.3 Assessment of Facility Functions

6.3.1 Importance of the assessment of facility functions

Subsurface dams are constructed underground and their facilities are designed based on the results of predictive simulations. These facts suggest that subsurface dam facilities have functional uncertainties. Accordingly, from the point before the start of construction through to the point after the completion of facilities, various surveys including groundwater level observation must be conducted to assess whether or not each facility has the required functions. If the survey results lead to the conclusion that the facilities are inadequate in terms of function and capacity, relevant measures must be taken if necessary. These measures include additional facility construction and changing of the operation method.

6.3.2 Assessment of cut-off wall functions

The data regarding the rising of the reservoir water level and the lowering of the groundwater level in the downstream side of the dam axis, both of which occur during the progress of the construction of the cut-off wall, are important for the following purposes: to determine the water shielding performance of the cut-off wall and to estimate the storage ratio of the reservoir, the amount of groundwater recharge and other properties.

By measuring the water level in the upstream and downstream sides of the cut-off wall after the completion of its construction, the effect of the cut-off wall in damming up groundwater can be checked. In the presence of abnormal water leakage from the cut-off wall, the location can be detected by determining where the water level is locally reduced immediately upstream of the cut-off wall. The trends in the groundwater table shape within the reservoir area must also be identified to check if there are any hydraulic problems.

In saltwater infiltration prevention dams, the salinity of reservoir water must be measured to check whether or not the cut-off wall is demonstrating the effect of preventing saltwater infiltration. When the cut-off wall is being partially constructed, the pattern of the groundwater flow within the reservoir area may change; more specifically, groundwater may flow from the upstream direction into the reservoir area and push saltwater masses within the reservoir area out toward the downstream direction of the dam axis. A phenomenon like this can be detected by measuring the salinity of groundwater within the reservoir area and downstream reaches of the dam axis.

6.3.3 Assessment of drainage facility functions

Drainage facilities are designed based on flood analysis that uses simulation technology. However, various parameters used for the flood analysis include uncertainties associated with the ground heterogeneity and the limitations of survey methods. This fact suggests the possibility that the estimates derived from drainage analysis regarding the amount of rise of the reservoir water level and designed amount of drainage may differ from the reality. Accordingly, after the installation of drainage facilities, observation including that of the reservoir water level must be performed continuously to check the effect of drainage facilities and assess the drainage plan.

It is necessary, when a heavy rain is anticipated after the completion of subsurface dam construction, to establish an adequate observation system to obtain data including the groundwater level, perform flood analysis using the data and examine the analysis results. If the drainage plan is inadequate, relevant measures must be taken such as additional installation of drainage facilities.

6.3.4 Large-scale water intake test

By performing a large-scale water intake test at the maximum reservoir level reached following the completion of the cut-off wall, the subsurface dam properties and intake facility capacity can be checked. This water intake test involves simultaneous operation of a large number of intake facilities for continuous water pumping to reduce the reservoir water level. The pumped water is drained outside the catchment area such as to the downstream side of the dam axis. The water intake test is performed for the following purposes:

(1) To estimate the storage ratio of the reservoir based on the amount of lowering of the reservoir water level caused by water pumping.

(2) To check how much the intake capacity is reduced by the lowering of the groundwater table by simultaneously operating a large number of intake facilities and thus reducing the groundwater level in the entire reservoir area as well as to determine how intake facilities interfere with each other.

(3) To check the water shielding performance of the cut-off wall by performing a water intake test that causes differences in the groundwater level between the upstream and downstream sides of the cut-off wall and that measures changes in the salinity of groundwater in the upstream side. This is only applicable to saltwater infiltration prevention dams.

During the water intake test, the groundwater level must be reduced in the entire reservoir area. However, if the amount of groundwater recharge is anticipated to almost equal the amount of water intake during the test period due to high precipitation, the reservoir water level may not be reduced. In this case, water must be continuously pumped for a considerably long period (one to two months) particularly during a period of low rainfall, in order to reduce the reservoir water level to a minimum. Ideally, the water intake test would reduce the reservoir water level to a minimum. However, the reality is that reducing the reservoir water to that level is often difficult. This necessitates the analysis of the relationship between the reduction of the water level achieved and the amount of water intake in order to extrapolate the hydraulic constants of the reservoir and intake facility capacity at the minimum reservoir level. Additionally, the water intake test may be carried out in parts, to compare and analyze the results of the water intake test carried out under different conditions, for example, in terms of water intake amount and precipitation.

The relationship among various parameters used for the water intake test can be expressed by the following equation.

$S = (Q+Or+Lk-Rc) / (\Delta V)$ $\Delta V = \Delta h x A$

S: Storage ratio of the reservoir, Q: Amount of water intake during a specified period

Lk: Amount of leakage from the cut-off wall, Rc: Amount of groundwater recharge

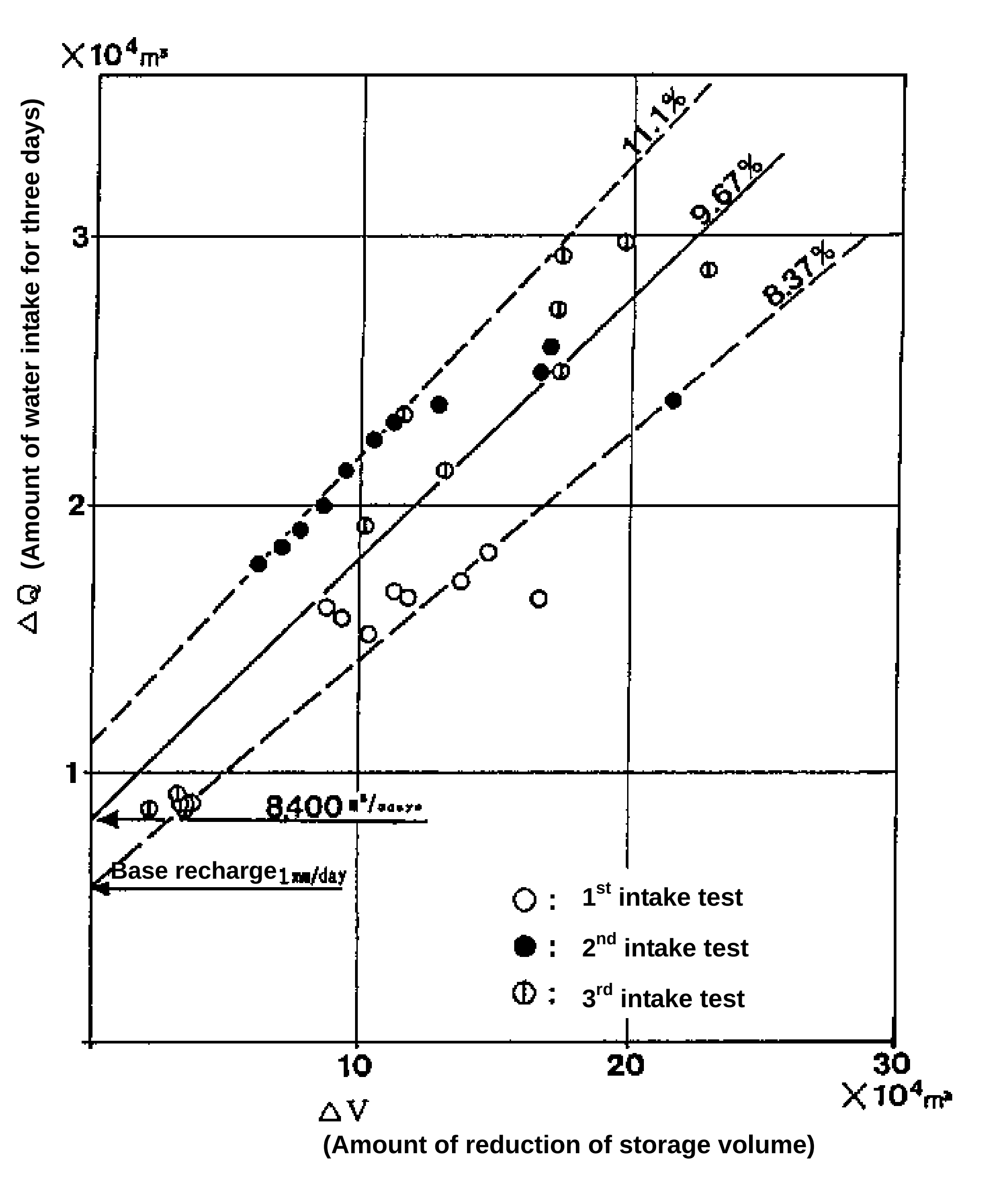
ΔV: Amount of reduction of storage volume, Δh: Amount of lowering of the reservoir water level, A: Storage area

Or: Amount of overflow from the cut-off wall (Or = 0 when the groundwater level is at or below the top of the cut-off wall)

Among the parameters used in the equation above, time-series data on the amount of water intake and the amount of lowering of the reservoir water level (amount of reduction of storage volume) can be obtained from the water intake test. If using the data obtained when the groundwater level is at or below the top of the cut-off wall and thus the amount of overflow from the cut-off wall is zero, the storage ratio, amount of groundwater recharge and amount of leakage from the cut-off wall are regarded as unknown. If no heavy rainfall is experienced during the test period, the amount of groundwater recharge and the amount of leakage from the cut-off wall are generally considered constant during a specific short period of time. The storage ratio can be obtained by solving simultaneous equations for periods with different amounts of water intake, with the amount of groundwater recharge, amount of leakage from the cut-off wall and storage ratio regarded as unknown.

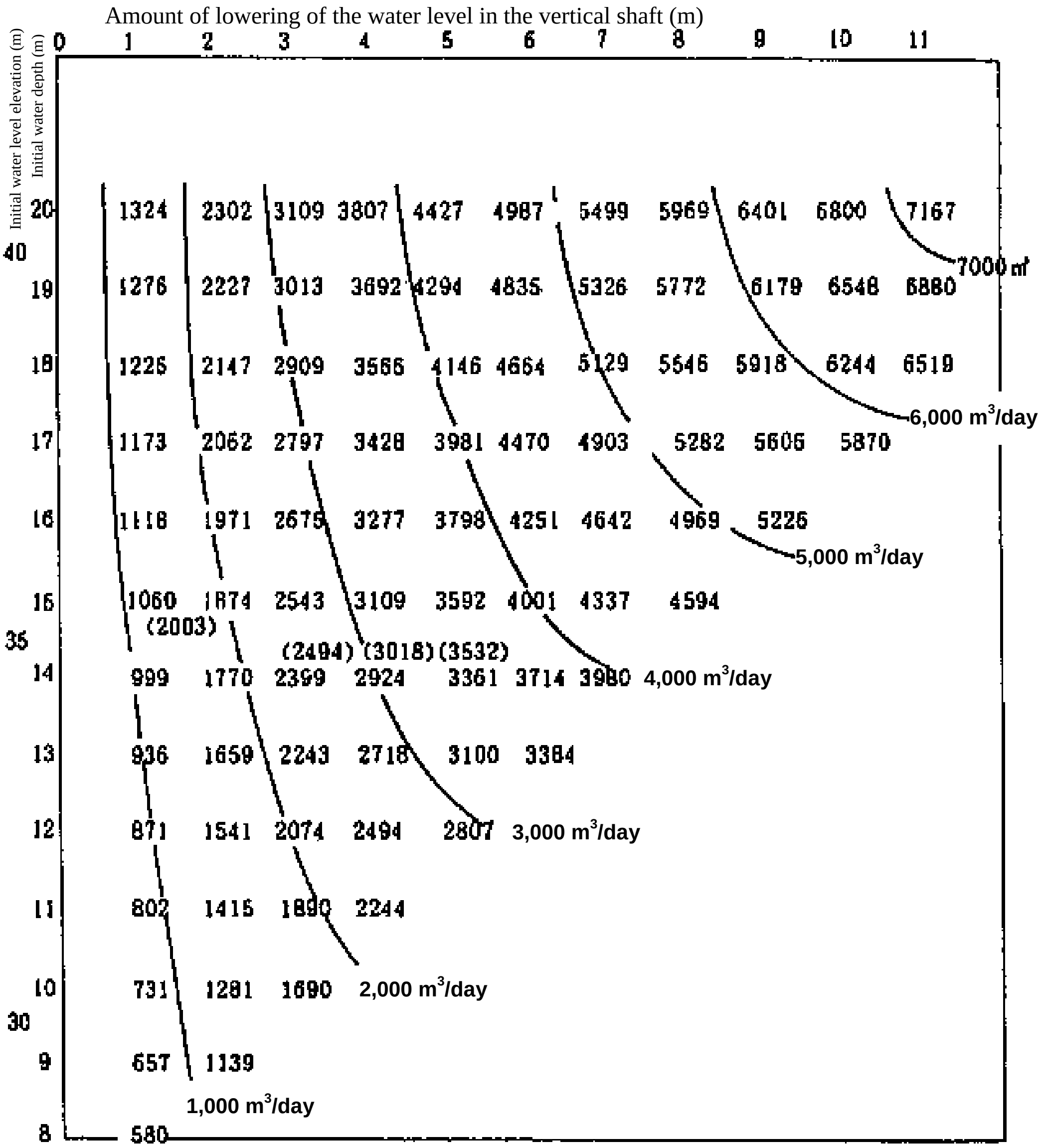
In the Minafuku subsurface dam, a large-scale water intake test was conducted four times. During each water intake test, an average of 2,000 to 8,000 m^3/day of water was pumped continuously for a period of 18 to 52 days. Figure 6.3.1 shows the relationship between the amount of reduction of storage volume (ΔV) and the amount of water intake (ΔQ) measured every three days plotted on the graph. The relationship was determined from the results of the water intake test (three times). The inclination of the straight line represents the storage ratio, while the intercept with the axis of ordinates represents the amount of groundwater recharge and the amount of leakage from the cut-off wall. The graph suggests that limestone forming the reservoir has a mean effective porosity (storage ratio) of 8 to 11%. It also became clear that the amount of groundwater recharge from catchment areas is 1 to 2 mm/day even after extended periods of no rainfall.

Figure 6.3.1 Relationship between the Amount of Water Intake and the Amount of Reduction of Storage Volume in the Minafuku Subsurface dam



The Minafuku subsurface dam has a horizontal collecting shaft for water intake that leads to the reservoir area from the vertical collecting shaft immediately downstream of the cut-off wall. During the 4th water intake test, the amount of water intake from the horizontal collecting shaft was changed in four levels to observe the groundwater level around the vertical and horizontal collecting shafts. Using the observation results and equations for calculating the designed amount of water intake (Sugio's and Manning's equations), the radius of influence of water intake and the hydraulic conductivity of the reservoir were calculated. The calculation produced the radius of influence of 400 to 500 m and hydraulic conductivity of 0.2 to 0.29 cm/sec. Using these results and the equations for calculating the designed amount of water intake, the relationship among possible amount of water intake, initial water level and amount of lowering of the water level in the vertical shaft was determined as shown in Figure 6.3.2. Thus, it became possible to quantitatively assess the reduction of the intake capacity of the horizontal collecting shaft as a result of reduced reservoir water level.

Figure 6.3.2 Calculation of Water Intake Capacity of the Horizontal Collecting Shaft in the Minafuku Subsurface dam



Chapter 7 Maintenance and Management

The management of the subsurface dam is classified into facility management and reservoir water management (catchment area management). Facility management is intended to ensure that various facilities such as the cut-off wall, intake facilities, drainage facilities and groundwater aquifer charging facilities can demonstrate the required functions. Reservoir water management, on the other hand, is intended to determine the reservoir water level (reservoir capacity) to perform proper water intake and drainage, and at the same time, to maintain water quality required for each purpose.

In the saltwater infiltration prevention dams, the state of saltwater infiltration into the reservoir area and of the saltwater masses remaining in the reservoir area must be determined during the operation of each subsurface dam. Moreover, when deemed necessary, the amount of water intake must be controlled to maintain the reservoir water at an appropriate level. It is important at the same time to use, for example, desalting facilities, to remove saltwater from within the reservoir area to reduce the salinity of the reservoir water to or below the allowable limit. The table below shows management activities in subsurface dams.

Management Item		Purpose and Detail of Management	Management Method
Facility management	Cut-off wall management	Determination of the amount of leakage from the cut-off wall Determination of the point of water leakage resulting from damage to the cut-off wall and other problems	Observation of the groundwater level in the upstream and downstream sides of the cut-off wall and other methods
	Intake facility management	Maintenance of the function of intake facilities and their renewal	Measurement of the amount of lowering of the water level during water intake and other methods
	Drainage facilities management	Maintenance of the function of drainage facilities	Observation of the reservoir water level Measurement of the amount of drainage and other methods
	Management of other facilities	Maintenance of the function of groundwater aquifer charging facilities, operation and maintenance facilities and other facilities	
Reservoir water management	Water intake management	Determination of the reservoir water level (storage) Optimum allocation of the water intake amount among intake facilities to ensure proper operation of these facilities	Observation of the reservoir water level Measurement of the amount of water intake Operation of intake facilities and other methods
	Drainage management	Determination of the reservoir water level, for example, during a heavy rain Determination of when to start draining and how much to drain, for example, during a heavy rain, to implement proper drainage	Observation of the reservoir water level Operation of drainage facilities and other methods
	Water quality management	Maintenance of reservoir water quality required for each purpose Determination of the state of saltwater infiltration Proper desalination of reservoir water	Observation of water quality in the reservoir area Water quality conservation measures in catchment areas Operation of desalting facilities and other methods

The most important factors for subsurface dam management are the determination and control of the groundwater table. Since groundwater flow is far slower than surface water flow, the subsurface dam, unlike the surface dam, has an uneven water surface (groundwater table) in the reservoir area, meaning that the water level varies by location in the reservoir. Water pumping in particular causes a reduction locally of the water level in the reservoir area. However, it takes a while before the changes in the groundwater table affect the surrounding area. When the reservoir surface rises, for example, due to heavy rain, a peak time lag often occurs. In-depth understanding of groundwater characteristics is required to perform subsurface dam management operations.

7.1 Maintenance and Management System

7.1.1 Establishment of a Managing Organization

It would be ideal for beneficiaries to play a central role in the maintenance and management of subsurface dams. However, the operation of the subsurface dam involves the running of intake facilities and drainage facilities, which are subjected to highly unpredictable natural factors. Uncertainties also exist with regard to whether each facility can perform its function as designed. It is, therefore, recommended that a group of advisers comprising technical experts be included in the managing organization in order to respond to situations that are unforeseeable during the planning and design stages.

Japan stipulates that various facilities of subsurface dams constructed for agricultural purposes should be managed and operated by agricultural land and irrigation associations – the beneficiary groups.

The Miyako district introduced water management regulations that clearly define where facility management responsibility lies; the responsibility for managing major facilities such as subsurface dams and trunk waterways belongs to agricultural land and irrigation associations and the responsibility for managing terminal irrigation facilities on cultivated land belongs to beneficiaries. From among these beneficiaries, one water administrator should be appointed for every 50 ha of area, to perform general management of water use in the district.

7.1.2 Management Regulations

When the following situations occur in subsurface dams, quick measures are needed.

(1) A heavy rain, for example, has caused the reservoir water level to rise beyond the high-water level or the increased reservoir water level may exceed the high-water level.
(2) A drought, for example, has caused the reservoir water level to fall below the minimum reservoir level or water shortage may occur in the future.
(3) An earthquake has occurred and may have caused damage to the cut-off wall and other facilities.
(4) A serious facility problem has occurred.

Subsurface dam management includes the operation of facilities under normal conditions as well as safe and proper operation of facilities under emergency situations as described above. It is also necessary to determine the present state of the subsurface dam, and at the same time, to investigate the meteorological, hydrometeorological, water quality and cut-off wall conditions and how intake facilities are being operated, and record and analyze the obtained data in order to develop future operation policies. To this end, management regulations were introduced on the matters below.

(1) Administrators (Administration managers and managing organizations)
(2) Target facilities for management (Facility dimensions and other specifications)
(3) Subsurface dam dimensions (Full reservoir level, low-water level, gross reservoir capacity, active capacity, high-water level and other)
(4) Water use rules (Period and amount of water use, water distribution method and other)
(5) Matters concerning facility inspection and maintenance (Inspection method, repair and renewal methods and other)
(6) Matters concerning observation and investigation (Items, quantities, frequencies and methods of observation and investigation, recording method and other)
(7) Measures to be taken under emergency conditions (Systems and actions under emergency conditions)

7.1.3 Coordination of Rights

In relation to the construction and operation of subsurface dams, the coordination of various rights may be required such as the setting of rights on subsurface structures, the coordination of water use rights between surface water and groundwater users within the same catchment area, and the coordination of rights with new developers in the same catchment area. With regard to the coordination of these rights, the presence or absence of problems must be identified and action policies must be formulated in the planning stage. Proper actions must also be taken in this regard as part of management responsibilities.

(1) Setting of rights on subsurface structures

Excavating the ground on the dam axis following the installation of the cut-off wall may pose risks such as damage to the cut-off wall or impairment of the permeability of the overflow crest. Structures such as buildings, if installed on the dam axis, may also become an obstacle when repair of the cut-off wall is necessary. For the protection and management of the cut-off wall, therefore, it is preferable to set a right on the use of land where the cut-off wall is located, in order to place restrictions on activities such as ground excavation and facility installation.

Two options are available when setting the land use right: either to acquire ownership that includes the right to use the ground surface or to acquire partitionary superficies only for the use of subsurface space. The first option – the acquisition of ownership that includes the right to use the ground surface – is employed when planning to use the ground surface as roads and other infrastructure for management purposes as part of facility management. On the other hand, when planning to use the second option –

the acquisition of partitionary superficies – it must be ensured, for example, that there is no construction on the ground surface that may cause problems to the maintenance, management and renewal of subsurface dam facilities.

In both the Sunagawa and Fukusato subsurface dams, a large part of the cut-off wall was sited below roads to assure the protection and easy management of the cut-off wall. Partitionary superficies was also acquired on private land (excluding roads) to protect the land use right on areas of construction of the cut-off wall and overflow crest and peripheral areas for the protection of these structures.

(2) Coordination with groundwater users

In the subsurface dam reservoir areas or lower reaches of the dam axis, the construction and operation of subsurface dams may cause changes in the groundwater level and groundwater flow rate and the deterioration of water quality, thus making traditional use of groundwater difficult. The areal extent and degree to which these problems may occur must be estimated during the planning and design stages to take measures to reduce the impact, and at the same time, coordination with groundwater users must be fostered. It is also necessary to continuously observe and analyze the groundwater level, water quality and other factors, from before subsurface dam construction, in order to assess the impact of construction.

The measures to solve the problems may include the provision of compensation to groundwater users affected by subsurface dam construction. However, it must be remembered that the notion of compensation and the compensation system vary by region and that the manner in which compensation is provided and the action of providing compensation itself may have a detrimental effect not only on the subsurface dam project but also on development activities and measures carried out in the entire region. It is important in regions like this not to easily resort to the provision of compensation, but rather to carefully work on coordination with groundwater users, while examining other solutions at the same time.

There may be cases where it is necessary to coordinate with and regulate those planning to use groundwater in the subsurface dam for new commercial applications within the same catchment area. In Japan, there are many examples where ordinances and other regulations are in place to promote coordination and regulation of groundwater use within the area served by one subsurface dam.

(3) Coordination with new developers within the same catchment area

Measures such as coordination and regulation must be taken for those planning to carry out development activities in the subsurface dam reservoir area that may have a detrimental effect on the function of the subsurface dam. Specifically, potentially detrimental development activities include the collection of ballast stones within the reservoir area, surface water intake that may affect groundwater recharge, and mining and tunneling excavation. The installation of drainage work to remove surface water in particular may reduce the amount of groundwater recharge to the subsurface dam reservoir area. One example of a measure used to solve situations like this is the connection of a drainage terminal to the infiltrating ground surface within the catchment area in order to prevent a reduction in the amount of groundwater recharge.

7.2 Facility Management

7.2.1 Management of the Cut-off Wall

The management of the cut-off wall includes making sure that its water-shielding performance is maintained and in the event of water leakage caused, for example, by damage to the cut-off wall, identifying where water is leaking from to take measures such as repair of the cut-off wall.

Water leakage from the cut-off wall results from either poor construction quality of the cut-off wall or damage after construction completion. Problems potentially associated with poor construction quality include wall hydraulic conductivity lower than the designed value, discontinuous cut-off wall and inadequate wall thickness, wall depth and penetration part length. Damage to the cut-off wall, on the other hand, results from the following causes:

(1) Increased permeability due to wall deterioration
(2) Eluviation and washout of wall materials
(3) Seepage failure of the wall or basement
(4) Damage to the wall due to abnormal stress
(5) Fissures generated by seismic shock
(6) Damage caused by ground displacement such as active fault, landslide and land subsidence
(7) Damage caused by artificial excavation

Among the causes listed above, (1) to (3) can be removed by taking additional precautions during the design and construction stages. Since the cut-off wall is normally supported by the ground on the upstream and downstream sides, it is unlikely that the wall would come under severe stress. However, there may be cases where it is difficult to estimate how much stress is being applied to the cut-off wall, particularly in hollow space areas. Accordingly, it is advisable to examine the possibility of (4) occurring. Items (5) and (6) are mainly caused by natural phenomena. It is assumed that among these causes, damage by earthquake is most likely to occur.

Since subsurface dams have their cut-off wall installed underground, leakage locations cannot be directly inspected or confirmed. This makes it necessary to measure the groundwater level, flow direction, flow velocity and other factors within the reservoir area and in the downstream of the cut-off wall to indirectly estimate where water is leaking from. Additionally, in the subsurface dam of saltwater infiltration prevention, there may be cases in which the point of water leakage in the cut-off wall or basement can be identified by measuring the salinity of groundwater in the upstream and downstream of the cut-off wall.

If damage to a part of the cut-off wall occurs below the reservoir water level, causing water leakage, a reduction in the reservoir water level is observed around where the water is leaking, causing a rise of the groundwater level in the downstream of the cut-off wall. As this shows, by observing the groundwater level in the upstream and downstream of the dam axis, it is possible to detect where water is leaking from. However, if the reservoir water level is high and groundwater is flowing over the cut-off wall, it is often difficult to detect where water is leaking from. On the other hand, when the reservoir water level is low, damage that has occurred in the upper part of the cut-off wall cannot be detected. Accordingly, it would be ideal to perform groundwater level observation for the purpose of cut-off wall management during the period when the groundwater level is relatively high but below the full reservoir level.

Factors such as the scale of leakage targeted for detection, the organization of facility administrators, the system for running the organization and observation costs must be considered when establishing the groundwater level observation system and determining the number of observation wells and observation frequencies. In particular, immediately after the completion of the cut-off wall, relatively frequent observation of a larger number of wells is required in order to locate where construction quality of the cut-off wall is poor and from where in the basement water is leaking. After that, regular observation and additional observation when an earthquake occurs may be performed. Incidentally, when damage, for example, by an earthquake, has caused water leakage, it takes a while before a change is seen in the groundwater level in the observation well because of the interaction of a number of factors including the distance from where water is leaking from to the observation well, the amount of leakage and the hydraulic conductivity of the aquifer. It is therefore preferable, when an earthquake or other natural disaster has occurred, to perform inspection and observation immediately after, and again about ten days after and about a month after the disaster occurrence.

For the purpose of cut-off wall management, a proposal as outlined below was prepared for groundwater level observation in the Sunagawa and Fukusato subsurface dams.

(1) To perform regular monthly observations of observation wells in the upstream of the dam axis at 200-m intervals.
(2) To perform yearly observations of observation wells that can be used for measurements in the upstream and downstream of the dam axis.
(3) To perform observations of observation wells that can be used for measurements in the upstream and downstream of the dam axis when an earthquake with a seismic intensity of 4 or greater has occurred.

In both subsurface dams, for the purpose of checking the depth of the top of the basement along the dam axis, holes bored at about 40-m intervals along the cut-off wall upstream and downstream are used whenever possible as observation wells for the groundwater level.

If water leakage is detected through observation of the groundwater level, observation wells must be additionally set up, and a tracer test, single-hole flow direction and velocity test and other tests must be performed to more accurately locate where water is leaking from. The amount of leakage can be estimated from the amount of reduction in the groundwater level near the leak using hydraulic formulas such as the Theis formula. If the amount of leakage is so large as to hinder the use of subsurface dam reservoir water, remedial work of the cut-off wall must be performed.

Since the cut-off wall of the subsurface dam is normally embedded underground, it is possible that it may be difficult to locate from the ground surface after completion. For this reason, it is preferable to clearly define the location of the cut-off wall on a coordinate system with clear reference points, and at the same time, to place signs and other indicators on the ground surface above the dam axis to ensure easy identification of the cut-off wall location.

7.2.2 Management of Intake Facilities

To use groundwater in the subsurface dam, power is needed to transport the water to the ground surface. This therefore necessitates constant water intake management, and at the same time, expenses for the maintenance and renewal of facility functions. With regard to dam management, the maintenance and management of intake facilities have a large weight in terms of labor hours and cost.

The measures to maintain functions include daily recording of the pumping rate and operating water level, and the inspection of the presence or absence of abnormal sound and vibration and water leakage from the flange and other parts. If using electricity as the power source, the operating current, voltage and insulating resistance values and other relevant values must be recorded. Moreover, routine inspection of pump units is required to replace consumables and perform repair work. When a pump has deteriorated in performance beyond the point where it can be used, the pump must be renewed. However, since considerable expense is involved, renewal must be made systematically when a large number of pumps are used.

Intake facilities experience drastic changes in groundwater flow velocity and pressure when pumping groundwater from the aquifer. This makes it likely that the parts in contact with the aquifer are susceptible to functional problems such as clogging. These problems, for example, cause excessive declines in the groundwater level during water intake, making it impossible to achieve required levels of water intake. It is necessary, with regard to the management of intake facilities, to detect abnormal water intake conditions and take required measures to maintain the function of intake facilities.

Groundwater contains dissolved bicarbonates such as calcium and magnesium. Reduced pressure due to pumping causes the release of carbon dioxide, and this changes the soluble bicarbonates carbonates that are hard to dissolve. The carbonates form scale that accumulates on the screen and surrounding area and causes clogging. The accumulation of scale, if found, must be removed by chemical processing using, for example, phosphoric acid. Dissolved compounds in water such as Fe^{2+} and SiO_2

in addition to bicarbonates often deposit around the slit, causing clogging of the screen. Screens with steel slits are susceptible to clogging as a result of slit corrosion. Chemical processing using phosphoric acid is also used to remove this kind of clogging.

Iron bacteria and other microorganisms that thrive in intake facilities may cause a sudden clogging of the screen due to the slime-like product they generate. This problem can be solved by forcing chlorine gas directly into the well or charging calcium hypochlorite (or sodium) into intake facilities for sterilizing purposes.

There are also cases where sand inflow from the aquifer and granular filler materials may cause physical clogging of the slit. This problem is specifically caused by the following reasons: the degree of agglomeration of the aquifer is low, the filter is not demonstrating its function, and excessive pumping has caused rapid increases in the groundwater flow rate during water intake. Filling the gap between the screen and porous wall with filler materials such as gravels of appropriate size can reduce the inflow of sand. To reduce the amount of sand inflow after the completion of intake facilities, it is necessary to reduce the pump discharge to lower the rate of groundwater inflow. In the event of a large amount of sand inflow, sand present in intake facilities must be discharged regularly.

The clogging in the screen in tubular wells can be removed by mechanical methods such as swabbing and jetting. Since mud from drilling may also cause clogging, special care must be used during the finishing of intake facility installation.

The removal of clogging in tubular wells for functional rehabilitation should ideally be carried out before the specific capacity of a well drops to or below 80% of the initial capacity. A well with a specific capacity that has dropped to or below 50% of the initial capacity is believed to be irrecoverable in many cases, no matter what measures are taken.

7.2.3 Management of Drainage Facilities

With regard to drainage facilities, the reservoir water level must be observed continuously to confirm whether drainage facilities are functioning normally. Particularly when an increase in the reservoir water level is anticipated, for example, due to a heavy rain, groundwater observation must be supplemented by the survey of the subsurface dam reservoir area, in order to confirm the presence or absence of damage caused, for example, by flooding. The inspection of drainage facilities must also be performed regularly to maintain proper functioning of the facilities. Particularly with regard to facilities embedded near the ground surface such as underdrains, whether or not ground excavation has caused damage to the facilities must be checked during a routine site patrol.

To ensure proper functioning of drainage facilities, it is a must that water is drained with no ponding from the terminal drainage port or drainage channel. Particularly when using a river bed for draining, accumulated sediment is often found shallowing the drainage channel or raising the bottom of the drainage channel. There may also be cases where a drainage port, being submerged, is unable to demonstrate its drainage function properly. The drainage port may also be clogged by sediment. For these reasons, it is necessary to inspect the drainage port and drainage channel, and if necessary perform dredging and cleaning.

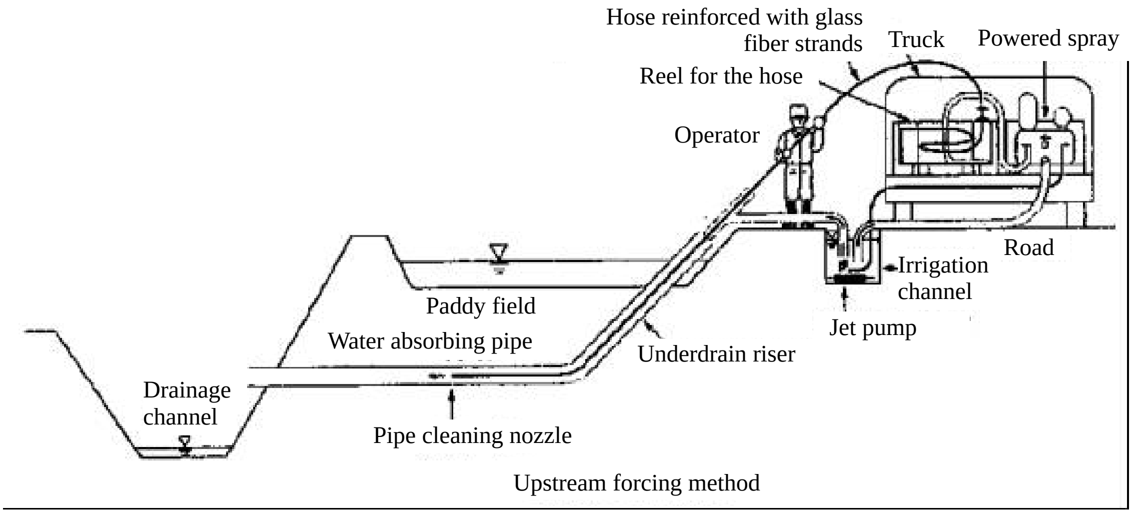
When installing underdrains for use as drainage facilities, maintenance and management must include the cleaning of underdrain pipes. The following factors are considered to be the causes of underdrain malfunctioning:

(1) Poor drainage, for example, due to clogging and damage to the underdrain pipe
(2) Clogging in filter materials
(3) Poor permeability resulting from discontinuity in the connection of underdrain pipes due to poor construction, and from insufficient charging of filter materials

If the soil around the area where underdrain pipes are set up easily migrates, it flows into the underdrain pipes and accumulates there. Deposits of iron hydroxide and other compounds may also cause clogging. If these problems have caused a deterioration in drainage performance, the underdrain pipes must be cleaned. Surface water is led into the underdrain pipes for cleaning. Figure 7.2.1 shows an example of a cleaning method that uses a reinforced elastic hose (such as a hose reinforced with glass fiber strands) with a cleaning nozzle at the tip, which is forced into underdrain pipes to eject high pressure water. Surface water is led into the underdrain pipes through the riser at the same time.

Clean water must be used for cleaning underdrain pipes so that the operation itself will not cause clogging due to the entry of impurities. One method to detect discontinuity between underdrain pipes uses a glass fiber strand or other similar material, which is inserted from the outlet or riser of underdrain pipes to check for points in the underdrain pipes where it is not penetrable. If cleaning fails to restore the underdrain function, reconstruction of underdrains must be considered.

Figure 7.2.1 Example of Removal of Clogging in Underdrain Pipes



7.3 Reservoir Water Management

7.3.1 Water Intake Management

The pumping yield from a tubular well is several thousand m^3/day at a maximum. To pump a large amount of water from a large-scale subsurface dam, therefore, a great number of tubular wells must be used. This necessitates complex management of the pump operating system. Particularly when the groundwater level drops locally within the reservoir area, some wells may be unable to produce water as planned, and this causes a deterioration of the intake capacity of intake facilities as a whole. To ensure, as much as possible, the uniformity of the groundwater level in the reservoir area, the amount of water intake must be properly apportioned to each well. Moreover, in the event of a drought, the current reservoir capacity and future water demand must be examined and appropriate water intake management must be performed to prevent water shortage.

To distribute water in the subsurface dam to a large number of beneficiaries, it is necessary to set up and observe water utilization rules such as regulations on the amount of water that can be used. However, a long dry season may affect the stability of the rules (for example, excessive pumping violations may occur), and this may lead to problems such as water shortage and unequal water use. To ensure fairness in water use, the observation of rules is most important. At the same time, the introduction of a flow control system to the division works is another option to achieve this end.

7.3.2 Drainage Management

Drainage methods are classified into two categories: natural drainage by means of overflow from the top of the cut-off wall or through drainage facilities, and forced drainage by means of pumping to drainage wells (which may also serve as intake wells).

If opting to use forced drainage as the drainage method, regulations concerning the criteria for operating drainage facilities, such as the water level at which to start drainage, must be established. Forced drainage, on the other hand, must be performed based on the following criteria:

(1) When natural drainage is not likely to reduce the reservoir water level
(2) When a long period of large rainfall is likely to cause the water to exceed the high-water level (preliminary drainage)

Since groundwater acts more slowly than surface water, measures taken after a problem has occurred may prove too late in some cases. To prevent the occurrence of flood damage, it is important to incorporate forecasts when determining control water levels.

7.3.3 Water Quality Management

To ensure water quality required for each purpose, the management of reservoir water quality must be performed. Water quality management is comprised of water quality survey designed to determine the trends in reservoir water quality and water quality conservation measures conducted in the subsurface dam reservoir area.

(1) Water quality survey

Water quality survey includes routine collection of reservoir water samples and water quality analysis of the specified items to determine the trends in reservoir water quality. Water quality analysis is conducted on-site or in the laboratory. On-site analysis may include, when using portable measuring instruments, the measurement of temperature, pH, electric conductivity and other properties. Simple water quality analysis methods have recently become available, including pack testing to enable quick and easy on-site analysis using reagent-filled test tubes. To analyze items that undergo significant changes with time, self-recorders may be used to continuously measure and record water quality data obtained from a sensor installed in the observation well. To perform highly accurate analysis of major ions, nitrogen, organic matter and bacteria, laboratory analysis must be performed using collected specimens.

Although the items that must be analyzed during a water quality survey vary by groundwater application, they generally include Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, Fe, NH_4^+, NO_3^-, NO_2^-, total dissolved solids (TDS), hydrogen ion concentration (pH), electric conductivity (EC), bacteria and colon bacillus. If the presence of farmland within the catchment area causes concern over the contamination of reservoir water by agricultural chemicals, the items for analysis must also include the agricultural chemicals used in the area. In the presence of mines and factories within the catchment area, on the other hand, the items for analysis must additionally include heavy metals anticipated to be released from such mines and factories.

To collect water samples from a bored hole, a small-diameter pump or throwing-type water sampler for narrow wells must be used. The specimens, when collected, must immediately be placed in sealed containers, transported in a refrigerated state to prevent quality changes and analyzed without delay.

Electric conductivity is the reciprocal of electric resistivity, and the larger the amount of total salts dissolved in water, the higher the electric conductivity. Electric conductivity can be readily measured and considered as a representative index of water quality. Water with high electric conductivity, which means a large amount of total dissolved salts, is often not suitable for drinking or irrigation purposes.

Groundwater samples collected from the same observation well but from different depths may have different quality, depending on the aquifer property or groundwater density. In a case like this, an observation well with a screen set up at different depths must be used to perform water quality observation at different depths. Particularly in the subsurface dam of saltwater infiltration, salinity must be observed horizontally and at different depths, to determine the three-dimensional distribution of salinized groundwater.

The analysis results produced from water quality survey must be checked against the drinking water quality guideline of the World Health Organization (WHO) (Table 7.3.1) and the irrigation water quality criteria of the United States Department of Agriculture (USDA) (Figure 7.3.1) in accordance with the purpose of water use, in order to determine whether the results meet the required water quality criteria.

Table 7.3.1 Drinking Water Quality Guideline of WHO (Excerpt)

Item	Guideline Value
Sb	0.005 mg/liter
As	0.01 mg/liter
Ba	0.7 mg/liter
B	0.5 mg/liter
Cd	0.003 mg/liter
NH2Cl	3.0 mg/liter
Cl	5.0 mg/liter
Cr	0.05 mg/liter
Cu	2.0 mg/liter
CN	0.07 mg/liter
F	1.5 mg/liter
Pb	0.01 mg/liter
Mn	0.5 mg/liter
Hg	0.001 mg/liter
Mo	0.07 mg/liter
Ni	0.02 mg/liter
NO_3^-	50.0 mg/liter
NO_2^-	0.2 mg/liter
Se	0.01 mg/liter
U	0.002 mg/liter
E. coli or thermotolerant coliform bacteria	Must not be detectable in any 100-ml sample
Gross alpha activity	0.1 Bq/liter
Gross beta activity	1.0 Bq/liter

Figure 7.3.1 Irrigation Water Quality Criteria of USDA (USDA, 1954)

$$SAR = Na^{+} \Big/ \sqrt{(Ca^{2+} + Mg^{2+})/2}$$

C1: Can be used for almost all types of crops and soils.

C2: Can be used for soils with moderate leaching and crops with an intermediate degree of salt resistance.

C3: Cannot be used for soils with poor drainage and but can be used for crops with high salt resistance, if planted in soils with moderate drainage.

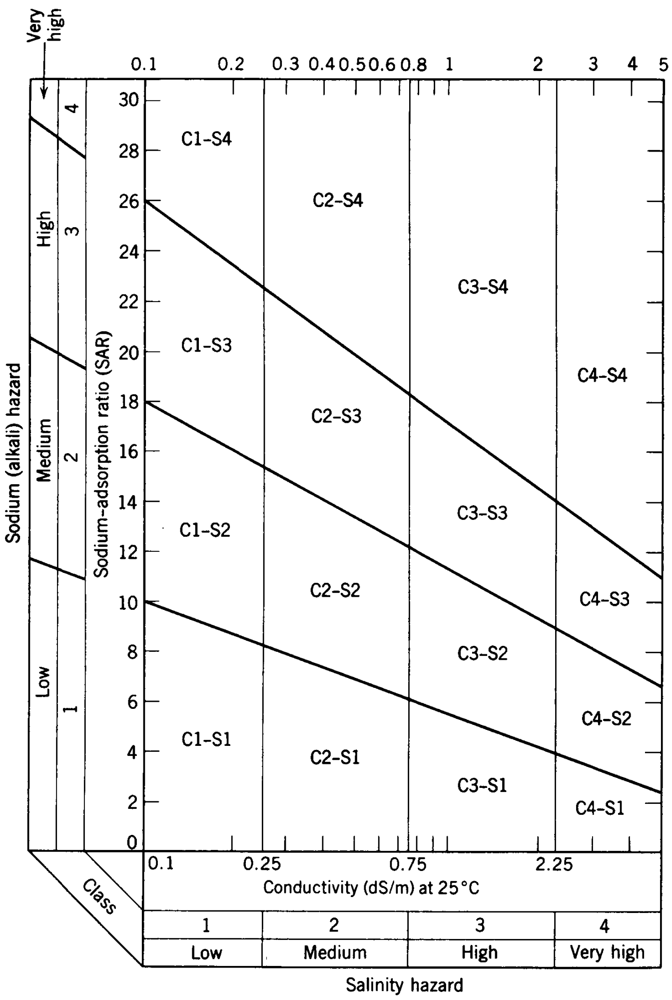
C4: Cannot be used for normal irrigation. Special measures against salt damage are needed.

S1: Can be used for almost all types of soils.

S2: Salt damage is obvious in granular soils with high cation exchange capacity.

S3: Salt damage occurs in almost all types of soils. Special soil processing, leaching and organic injection are needed.

S4: Not suitable for irrigation purposes.



In the subsurface dam of saltwater infiltration prevention, a certain amount of saltwater may infiltrate into the reservoir area through the cut-off wall or basement during the course of operations. After the installation of the cut-off wall, saltwater masses may be found remaining in the reservoir area. The salinity of reservoir water fluctuates under the influence of the saltwater. It is, therefore, necessary to first set an allowable limit of salinity, perform water intake management to keep the salinity of reservoir water within the allowable limit and limit the reduction of the reservoir water level. There may also be cases where groundwater that contains salt is mixed and diluted with water from other fresh water sources to increase its use.

When planning to use groundwater containing salt for agricultural purposes, salt resistance of crops and salt accumulation in soils are considered to be issues. The salt resistance of each type of crop is determined by how much influence is caused by salt absorbed from the soil and salt adhered to the stem and leaves. Salt resistance varies by crop type. Some highly salt-resistant crops can withstand salinity greater than 2,000 mg/lit, with no effect on their growth. In Japan, there is an example of a subsurface dam for agricultural purposes where the allowable limit of salinity (chlorine ion concentration) of reservoir water is set to 200–500 mg/lit.

(2) Water quality conservation measures for the subsurface dam reservoir area

It is generally the case that once contaminated, the reservoir and reservoir water in the subsurface dam do not recover easily. It is, therefore, important to prevent contamination, and if contamination has occurred, to prevent it from spreading. To protect the quality of subsurface dam reservoir water, activities that may affect water quality conducted within the subsurface dam reservoir area must be supervised, and at the same time, measures must be taken to discover and remove water contamination sources, and recover water quality. In some cases, laws, regulations and ordinances, for example, may be used to make it compulsory for those engaged in activities that deteriorate or may deteriorate groundwater quality in the catchment area to carry out required measures to protect water quality.

On Miyakojima Island in Okinawa Prefecture, where the Sunagawa and Fukusato subsurface dams were constructed, the increase in the amount of nitrate nitrogen in groundwater reached an unacceptable level. This problem was caused by the infiltration of fertilizers and daily life drainage. To solve this problem, various measures are being taken, including the installation of drainage treatment facilities, determination of the optimum amount of fertilizing, the introduction of a time lag in applying fertilizers and the use of slow-acting fertilizers.

Appendix

Glossary of Groundwater Development Terms

References used to define the terms in this technical reference are shown below.

- Dictionary of Civil Engineering Terminology (Japan Society of Civil Engineering)
- Technical Terms on Irrigation, Drainage and Reclamation (Japanese Society of Irrigation, Drainage and Reclamation)
- Drafted Technical Guidance on Subsurface Dam Planning and Design (Ministry of Agriculture, Forestry and Fisheries)

(1) Terminology related to subsurface dam facilities

Active capacity: The amount of groundwater obtained by subtracting the dead capacity from the gross reservoir capacity.

Aquifer charging facilities: Facilities that promote subsurface infiltration of surface water to increase groundwater recharge in the reservoir area, including ponds, ditches and wells.

Catchment area: The area that contributes runoff to the subsurface dam reservoir area when in a natural state.

Cut-off area: The sectional area obtained by subtracting the penetration part area from the dam sectional area.

Cut-off wall: A structure built in the aquifer to dam up groundwater. More specially, an artificial subsurface structure with a certain thickness constructed in a line similar to a wall that is less water-permeable than the aquifer.

Dam axis: The vertical section of the dam crest.

Dam crest: The crest of the cut-off wall.

Dam crest elevation: The elevation of the dam crest.

Dam height: The (maximum) height of the cut-off wall including the penetration part.

Dam length: The total length of the dam crest.

Dam sectional area: The longitudinal section area of the cut-off wall including the penetration part.

Dam width: The thickness of the cut-off wall.

Dead capacity: The amount of groundwater when the groundwater level is below the minimum groundwater table.

Drainage facilities: Facilities that drain water in the reservoir area required when the increase in the groundwater level may cause flooding and other damage, including open channels constructed on the ground surface and underdrains constructed underground.

Full reservoir level: The water level in the reservoir area when an overflow starts from the dam crest. However, the groundwater table is not exactly level.

Gross reservoir capacity: The amount of groundwater in the reservoir area at the full reservoir level.

Intake facilities: Facilities that allow access to groundwater stored by the cut-off wall, including wells, collecting wells, collecting side holes and collecting tunnels.

Minimum reservoir level: The depth of the minimum groundwater table that is reached as a result of groundwater use in the reservoir area. When groundwater is pumped up from a well, the minimum groundwater table falls in a funnel shape with the well located in the center.

Operation and maintenance facilities: Facilities that perform observation of the groundwater level and amount of rainfall to estimate the water level, and based on the estimation adjust the water level and determine whether water intake restrictions are necessary. If there are concerns over salt water infiltration, facilities that perform observation of salinity and remove salt are also required.

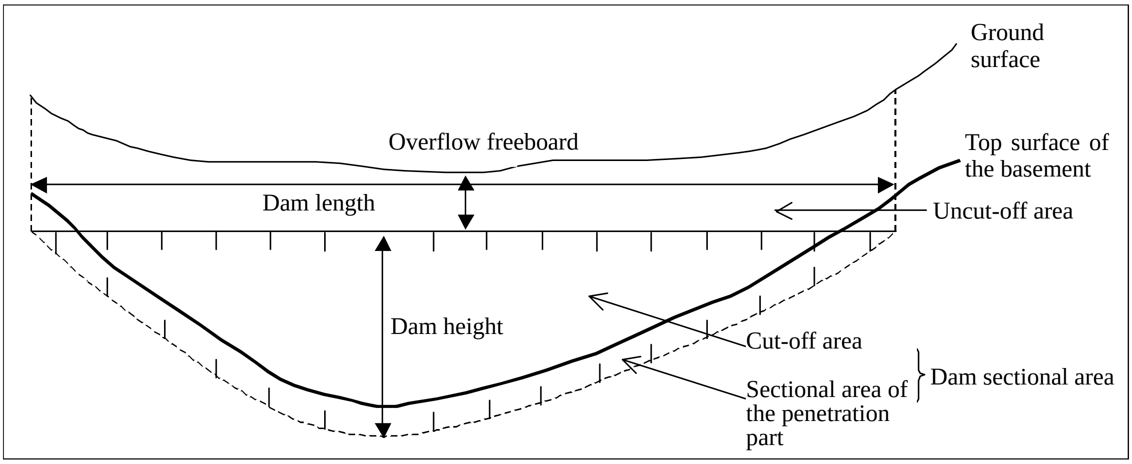
Overflow freeboard: Difference in elevation between the ground surface and dam crest at the point where they are closest.

Penetration part: The part of the cut-off wall penetrating into the basement.

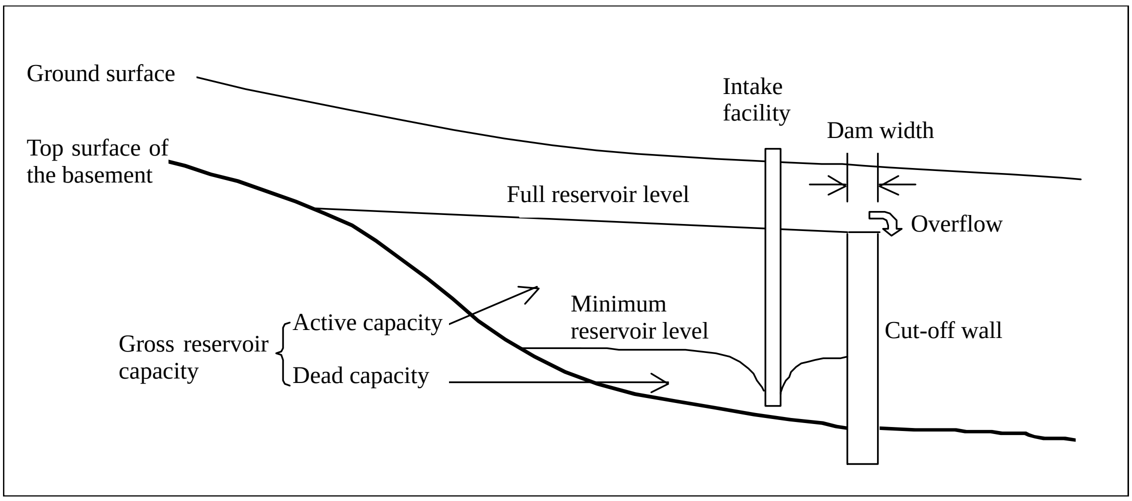
Reservoir area: The area upstream of the cut-off wall holding groundwater.

Uncut-off area: Vertical sectional area between the dam crest and ground surface.

Sectional view of the cut-off wall



Sectional view of the subsurface dam reservoir area



(2) Aqueous environment

Absolute humidity: Weight of water vapor contained in a unit volume of atmosphere, measured in units of g/m^3.

Alkali degree: The degree of inclusion of hydroxides of alkali metals (K and Na) and alkaline earth metals (Mg and Ca). Groundwater contains higher concentrations of these metals than surface water and the degree of inclusion depends on the nearby soil type.

Aquifer: A water-saturated, permeable stratum.

Base flow: The balance of water when the surface runoff and subsurface runoff are subtracted from the total runoff, which runs underground in the downstream direction.

Basement: A bedrock or stratum with low water permeability.

Cavitation: A phenomenon of rapid vapor bubble formation in high-speed water flows due to localized pressure loss.

Coefficient of roughness: Coefficient of flow resistance of the pipeline wall surface or open channel.

Confined state: A state where pressure is applied between impermeable layers.

Consolidation: A phenomenon of volumetric reduction by gradual draining of gap water when low permeable material such as clay is placed under the load.

Creep length: The watercourse length when infiltrating water runs along the base of a non-water permeable structure.

Darcy's law: The law based on the principle that the water infiltration speed is proportionate to the hydraulic gradient.

Effective porosity: The volumetric proportion of water that can be drained from one aquifer to another.

Free state: A state free from coverage by an impermeable layer.

Gut: A waterway for the runoff of water.

Hardness: The level of calcium dissolved in water.

Head: Hydraulic energy expressed in terms of elevation. In the free state, this refers to the elevation of the groundwater table.

Hydraulic conductivity: An index of water permeability of the ground, expressed using the same unit of measurement as for the speed. Ground with lower hydraulic conductivity reduces the infiltration speed on the basis of the same hydraulic gradient. Since water movement in soil is also affected by soil water content, the hydraulic conductivity is expressed in two ways: the saturated hydraulic conductivity, the conductivity in the saturated state, and the unsaturated hydraulic conductivity, which is lowered with the reduction of water content.

Hydraulic gradient: The gradient of the groundwater table. More precisely, the inclination of the line of heads.

Hydraulics: A water path.

Hydrology: Water circulation and distribution, and physical and chemical characteristics of water.

Hydrostatic pressure: Static water pressure that acts vertically to a surface.

Indirect catchment area: The catchment area that does not allow natural runoff of water.

Influence area: The area susceptible to groundwater level decline due to well pumping.

Piping: The effect of moving soil particles using the force of infiltrating water and creating tubular pores in the ground.

Possible duration of sunshine: The time from when the sun rises from the eastern horizon to the time when it sets below the western horizon.

Potential evapotranspiration: Evapotranspiration when a sufficient amount of water is present on ground surface covered by plants.

Roundabout percolation: A state in which water infiltrates below a non-water permeable structure in a roundabout way.

Salt water infiltration: A state where in aquifers near the coast, sea water that has a large specific gravity penetrates into the landward side in a wedge shape below fresh water. The wedge angle varies depending on the fresh water pressure. A lower fresh water pressure increases the wedge angle to become almost horizontal, meaning that sea water penetrates deeper into the landward side.

Sedimentation: The accumulation within the storage reservoir of sediment that was transported into the storage reservoir.

Specific capacity: One of the indices of aquifer permeability, expressed by the pump discharge relative to drawdown (unit: $m^3/d/m$).

Steady state: A state in which there are no significant changes with time.

Storage coefficient: An expression of volumetric ratio between the amount of water drained from an aquifer and the amount of lowering of the groundwater table caused by the drainage. The storage coefficient of an aquifer in the free state is almost equal to effective porosity.

Subsurface runoff: A portion of rainfall that first infiltrates the surface layer but comes up to the earth surface again in the downstream direction.

Surface runoff: A portion of precipitation that flows directly over the ground surface.

Surging: A phenomenon of fluid waving due to a rapid increase in the flow rate.

Tri-linear diagram: A graph showing the composition of major ions in groundwater by cation (Na^++K^+, Ca^{2+} and Mg^{2+}) and anion (Cl^-, SO_4^{2-} and HCO_3^-).

Subsurface valley: A state where the basement lying below an aquifer is shaped like a valley.

Water content: The value obtained by dividing the weight of water in soil by the dry weight of the soil (%).

Well group theory: A theory to the effect that simultaneous pumping from multiple nearby wells causes a fall in water levels due to mutual interaction, resulting in a larger reduction of pump discharge than when the wells are individually pumped.

(3) Facilities and construction methods

Abutment: A part of the cut-off wall in contact with a natural mountain.

Admixture: Material other than cement, water or aggregate that is used in cement.

Age: The time that has elapsed since concrete or mortar was mixed.

Auger: An instrument used for digging into the ground.

Backfill: The filling of the back of subsurface structures with soil material.

Backwashing: The washing out of floating suspended matter using pressured water.

Bench cut: The chipping away of sediment to shape it like a staircase in order to create horizontal surfaces along a slope.

Bending moment: The couple of forces causing the bending of members.

Bentonite: A type of clay produced when volcanic rocks are chemically altered, characterized by excessive swelling or contraction due to water absorption or release. Often used in grouting as lubricant as it improves flowability.

Box culvert: A type of culvert with a box-shaped cross section. The culvert refers to the passage beneath roads and structures such as waterways.

Buckling: A phenomenon of rapid deformation of structures under compressive force exceeding a certain level in the direction perpendicular to the direction of force.

Casing pipe: A protective pipe for porous well walls.

Cast-in-place concrete pile: A type of pile formed by drilling a hole into the ground and filling the hole with concrete.

Cement milk: A milky suspension that is a blend of water and additives, used as a primary cement component.

Clamshell: A type of excavator, which has a grab bucket attached to a crane.

Collecting drain: A pipe used to collect and transport subsurface water (if present in an excessive amount) absorbed by the sub-lateral drain to the drainage channel.

Collecting well: A large-diameter well with a large number of laterally drilled holes used as a groundwater intake facility to effectively extract water from the nearby strata.

Counter-dam: A low-elevation dam designed to prevent erosion in the downstream slope of the main dam.

Couple of forces: The forces that produce rotations.

Curing: The maintenance of appropriate temperature and humidity to ensure proper concrete curing and protection from external forces.

Division works: A structure that distributes the diverted water to specific regions at specific flow rates or while maintaining specific water levels.

Embankment: The placing and compacting of cut-off wall material.

Filter material: Water-permeable material that improves absorption performance used as a part of the sub-lateral drain.

Flap gate: A flip gate that opens and closes according to the hydraulic pressure detected.

Fly ash cement: Cement produced by blending fly ash, fine silica material captured by the dust collector, with Portland cement.

Gabion: A rectangular basket filled with pebbles used, for example, for river bank protection.

Gravel pile: A column-shaped structure filled with gravel used to improve the water permeability of the ground.

Ground sill: A structure built across a river to stabilize the river bed.

Grouting: The injection of solidifying agents such as cement into foundation ground.

Hammer grab: A machine that drops a heavy bucket from several meters to excavate mountains.

H-type steel pile: H-shaped steel piles.

Inner section: The cross section of a hollow space within a hollow structure.

Jamming: A state where boring tools such as bits can no longer be pushed through during boring due to collapse of or push-out from the porous wall.

Leaks: The leakage of injected grout from somewhere on the ground surface.

Liner plate: A steel sheet pile with the four corners press-folded and flanged.

Load: An external force that acts on a structure.

Mortar: A blend of cement, water and sand, sprayed over grouting or structures.

Mud water: A solution that contains a large amount of bentonite, used for adjustment purposes during boring in order to protect the porous wall and cool the bit.

Multi-axial operating: A ground excavation method that uses multiple simultaneous rotary shafts.

Pick hammer: A hammer drill with a pointed chisel at the front edge to crush rocks, mainly used for soft rocks.

Pit: A gallery excavated vertically from the ground surface.

Punching shear: A localized fracture, for example, a cone-shaped puncture in a small region of a plate under intensive load.

Reference year for design: A particular past year used as reference for a project or structure plan. A plan is developed in consideration of meteorological and hydrological conditions in the particular year.

Rolled compaction: The application of static pressure by a heavy pressure roller.

Rotary percussion boring: Boring with drilling equipment with rotary and percussion drilling functions.

Rubble: Stones artificially broken into pieces of about 10 to 20 cm in diameter at a quarry.

Sand compaction pile: A sand column artificially set up in the ground in order to drain water from weak ground and compact and stabilize the ground.

Sand pump: A pump that sucks up and carries sand and mud together with water.

Screen: A net-shaped, porous device that removes suspended matter from water.

Sealing material: Material that prevents water leakage, for example, from joints.

Self-hardening slurry: A blended solution of water, clay, cement and other material, which naturally solidifies when left standing for many hours.

Shearing: An internal shear caused by external stress.

Sheet pile: A sheet-like structure set up to maintain ground stability, including steel sheet piles and concrete sheet piles.

Slag: Non-metallic residue produced from ore melting and refining.

Simple pipe rod method: A method that uses the boring rod as the filling pipe to force grout into the ground.

Sleeve pipe: A device with a double layer structure (an internal and external casing) and with many release openings on the lateral side of the internal casing, which slides open or closed when the external casing moves.

Soil cement: A mixture of soil and cement.

Spillway: A drainage facility that automatically releases surplus water in the dam and ensures safe flow of the water to the downstream reservation.

Stage grouting: One of the commonly used grouting methods, which divides the grouting hole length into segments of certain length and alternately performs boring and grouting to dig deeper into the ground. The method also uses a packer fitted to the target segment to prevent grout leakage.

Staggered arrangement: A state in which the grid is not square but staggered.

Starting bore-hole: The pre-grouted hole.

Strainer: A filter fitted to the water inlet to prevent the entry of sediment and dust from nearby areas, for example, during groundwater pumping.

Sub-lateral drain: A pipe or water-permeable material in use for drainage release at the end of the underdrain pipe.

Suspension: A solution with dispersed particles.

Temporary diversion facility: A facility temporarily set up to ensure the safety and rationality of river channel work, including temporary drainage channels that process river water.

Torque: The moment of the couple of forces.

Tremie pipe: A transport pipe used in underwater concrete casting.

Tunnel element: A tunnel-like structure submerged and connected in the trench excavated in the bottom.

Twin-pipe double packer method: A method of grouting through the filling pipe fitted with a double packer following the installation of an outer pipe in the bored hole.

Underdrain: A buried subsurface drainage facility.

Vibro-hammer: A hammer with a built-in vibrator.

Wing: The part to which the dam overflow falls.

(4) Survey method

Aerial photograph: A strip of photographs taken from above (vertically) from an aircraft at almost equal intervals. The photographs laid in order enable the analysis of various land information using a stereoscope.

Benchmark: A sign set up approximately every 2 km along main roads with the original benchmark set as the reference point. Each benchmark is located at different elevation points.

Collimation: The alignment of the telescope axis to the target.

Core boring: A method used to investigate subsoil properties using columns of soil and rocks collected during ground excavation. The soil and rocks are called the core.

Data logger: A device that automatically records measured values to allow their input as digital data to the computer.

Diamond bit: A diamond drill blade at the tip of the excavator.

Electric conductivity: An index of water electric conductivity. A higher ionic concentration increases the value of electric conductivity. The unit is mS (milli-siemens)/cm. Since the electric conductivity can easily be measured and is closely correlated with the chlorine ion concentration, the index is convenient for determining the extent of groundwater salinization in coastal regions.

Electric prospecting: A prospecting method used to estimate the subsurface distribution of specific-resistance, which involves the installation of electrodes on the ground surface to artificially induce electric currents in the ground.

Inclinometer: A measuring instrument that measures the inclination of the ground and structures.

Lugeon test: A test used to estimate the water permeability of the bedrock. More specifically, the amount of water injected into a 1-m segment of the bored hole under a steady pressure is measured and the value (Lugeon value) is expressed in units of l/min.

N-value: An index of soil hardness and compaction, expressed by the number of strikes required to bury a standard sampler 30 cm deep when using the free fall of a 63.5 kg hammer from a height of 75 cm.

Field permeability test: A test used to estimate the water permeability of a stratum by using the bored hole for water pumping or injection.

Pumping test: A test to observe the lowering of the groundwater level and the rising of the water level after pumping stops by pumping a given amount of water from a well. The test results are used to estimate the water permeability and retentivity of an aquifer.

Resistivity: A physical property value that indicates resistance to electric conductivity, namely, the electric resistance value per unit volume. The unit is Ωm. Different resistivity regions are found in soil.

Simultaneous groundwater level observation: The measurement of groundwater levels in a considerable number of wells in a short period of one or two days in order to determine the shape of the groundwater table.

Slime: Chips produced from excavation.

Specimen: Samples for various physical tests.

Transit: A survey instrument fitted with a telescope in order to measure the horizontal angle and angle of elevation.

Unconfined compression strength: Material strength determined by the unconfined compression test. Unconfined compression refers to the application of one-directional compressive force in the absence of laterally applied pressure. Based on this strength index, rocks are classified into soft, medium-hard and hard rocks.

Water level recording gauge: A device that automatically records water level changes continuously. Available in two types: the hydraulic pressure type for measuring changes in water pressure using a sensor placed at a given depth under water and the floating type for measuring vertical fluctuations of a float.

Water test: A simple Lugeon test that precedes grouting in order to investigate the degree of impervious improvement expected from grouting.

(5) Geological terms

Facies: The appearance of strata.

Geologic column: A figure showing soil stratigraphy and rock facies in a column, used to sort out the results of exploratory boring.

Ravine plain: A ravine area flattened as a result of sedimentary accumulation.

Rock facies: The appearance of rocks.

Stratigraphy: The order or arrangement of strata.

Talus: A topographic feature formed by the accumulation of rocks and sediment that fall away from steep slopes.

Volcanic breccia: A rock consisting of volcanic rock fragments, volcanic ash and sand.

Matrix: Granular material that fills the gap between rocks in a stratum.

(6) Analysis and calculation methods

Boundary condition: A condition that must be met by the function assumed in the analysis. For example, when in contact with a sea or lake, the water level must be maintained in a steady state and when using a ridge as a boundary, the absence of water inflow or outflow must be ensured.

Dispersion coefficient: The coefficient that affects the equation expressing the migration and dispersion of substances dissolved in groundwater.

Extrapolation: The estimation, based on a known function value within a domain, of a function value outside the domain.

Finite difference method: A method used to calculate an approximate solution of a differential equation. The difference, $dy = f(x+dx) - f(x)$, relative to an infinitesimal increment, dx, of a variable is called the difference in function. When dx is reduced infinitely close to 0, dy is the differential. The finite difference method is a digitized form of the differential equation. Reducing the limited range, dx, of a variable and increasing the number of dx's increases the amount of calculation.

Finite element method: A method used to calculate an approximate solution based on the function that represents an infinitesimal change in each nodal point of the element produced by arbitrarily dividing two- and three-dimensional regions.

Jacob's method: A method used to calculate the hydraulic conductivity and storage coefficient based on the equation proposed by Jacob, on the assumption that if the continuous pumping time is long enough, the logarithmic relationship between the amount of lowering of the water level and the continuous pumping time can be approximated by a linear transformation.

Parameter: Characteristic values used in equations.

Recovery method: A method used to observe and analyze the recovered water level after pumping stops. Hydraulic conductivity can be calculated using an equation that is derived from the equation proposed by Jacob on the assumption that the difference in water level from when pumping started is proportionate to the time that elapsed from when pumping started and to the logarithm of the time ratio after pumping stops.

Series tank model: An equation used to perform general analysis of the water balance in the catchment area.

Specific storage coefficient: A constant necessary for the analysis of subsurface infiltration in the non-steady state, which affects the increase or decrease of the amount of reservoir water relative to the change in effective stress caused by the change in the head.

Theis's method: An analysis method used for the pumping test based on the analytical model proposed by Theis. The non-steady state analytical model expresses the reduction of the water level that results from pumping at rated capacity from a homogeneous and isotropic confined aquifer with uniform thickness that infinitely expands horizontally.

Thiessen Method: A method used to calculate the depth of precipitation from rainfall data from multiple points. To estimate the regional rainfall, regions are divided into multiple polygons and the data from a central observation point is used to represent the rainfall within each polygon.

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