Technical Assistance for Improvement of Capacity for Planning of Road Tunnels
Japan Sri Lanka

Guideline for Environmental Impact Study (Groundwater)

February 2018

Road Development Authority (RDA)
Japan International Cooperation Agency (JICA)

Preface

This guideline summarizes the investigation and analytical method of the impact of tunneling work on groundwater. The purposes of this investigation and analysis are to forecast its impact, to take measures not to affect the groundwater, and to take measures to minimize its impact if it occurs. That is, it is the same as an environmental impact assessment (EIA). Therefore, the guideline summarizes the investigation and analytical method used according to the work process of the EIA.

This guideline has been developed based on the following:

- Guidance for Implementing the EIA Process, No.2: A general Guide for Conducting Environmental Scoping, Central Environmental Authority, Ministry of Environment and Natural Resources, Sri Lanka, 2003.
  < http://dl.nsf.ac.lk/ohs/cea/06409.pdf >
- EIA in Japan, Ministry of the Environment, Government of Japan, < https://www.env.go.jp/en/policy/assess/pamph.pdf >
- Technical guidance of EIA, Atmosphere, water and soil environment and environmental load (in Japanese), edited by Study group on EIA technique, supervised by Dept. EIA, General Environment Policy Bureau, Ministry of the Environment Government of Japan, 2017.
- EIA technology in the air, water and environmental load fields (I), How to proceed with scoping (in Japanese), Technical Committee on EIA Technology in the Atmosphere, Water and Environmental Load, 2000,
  < http://www.env.go.jp/policy/assess/4-1report/01_taiki/1.html >
- EIA technology in the air, water and environmental load fields (II), How to proceed with EIA (in Japanese), Technical Committee on EIA Technology in the Atmosphere, Water and Environmental Load, 2001,
  < https://www.env.go.jp/policy/assess/4-1report/01_taiki/2.html >
- EIA technology in the air, water and environmental load fields (III), How to proceed with Environmental Protection Measures, Evaluation and Follow-up Investigation (in Japanese), Technical Committee on EIA Technology in the Atmosphere, Water and Environmental Load, 2002,
  < http://www.env.go.jp/policy/assess/4-1report/01_taiki/3.html >
- Revised Groundwater Handbook (in Japanese), Editing Committee of Groundwater Handbook, 1998.
- Construction Work and Groundwater (in Japanese), edited by Japanese Geotechnical Society, 1998.

Table of Contents

Figures

Table

1 Introduction of EIA on groundwater

1.1 EIA Procedure

The National Environment Act[1] introduced an internationally accepted process called Environmental Impact Assessment (EIA) as part of the strategy to achieve sustainable development.

EIA is a simple and straightforward process of first predicting the potential impacts of development activities on the natural and social environment, and then suggesting measures to prevent or minimize negative impacts as well as enhance positive impacts.

EIA process involves 6 major steps; (i) screening, (ii) scoping, (iii) preparation of the EIA / Initial Environmental Examination (IEE) report, (iv) review of the report (by the public and the Project Approving Agencies (PAA)), (v) approval with terms and conditions or rejection with reasons, and (vi) post approval monitoring. These steps have been specified in the EIA regulations which have been published in Gazette No. 772/22 of 24.06.1993.

A flow diagram and a brief description of the EIA technical work process after Scoping is shown in Figure 1.1. The following technical work process is necessary to carry out the EIA:

a) Understanding of project characteristics
b) Regional outline investigation
c) Planning EIA (determination of areas, method and evaluation factors of investigation)
d) EIA investigation
e) Investigation during project implementation (conducted in parallel with the work from f to h.)
f) Forecast
g) Determination of environmental protection measures
h) Follow-up investigation

Although the EIA survey in item d) is generally called "investigation", it is called EIA investigation in this guideline to distinguish from the regional outline survey of b) and follow-up investigation of h).

[1] EIA procedure in Sri Lanka, http://www.cea.lk/web/index.php/en/environmental-impact-assessment-eia-procedure-in-sri-lanka

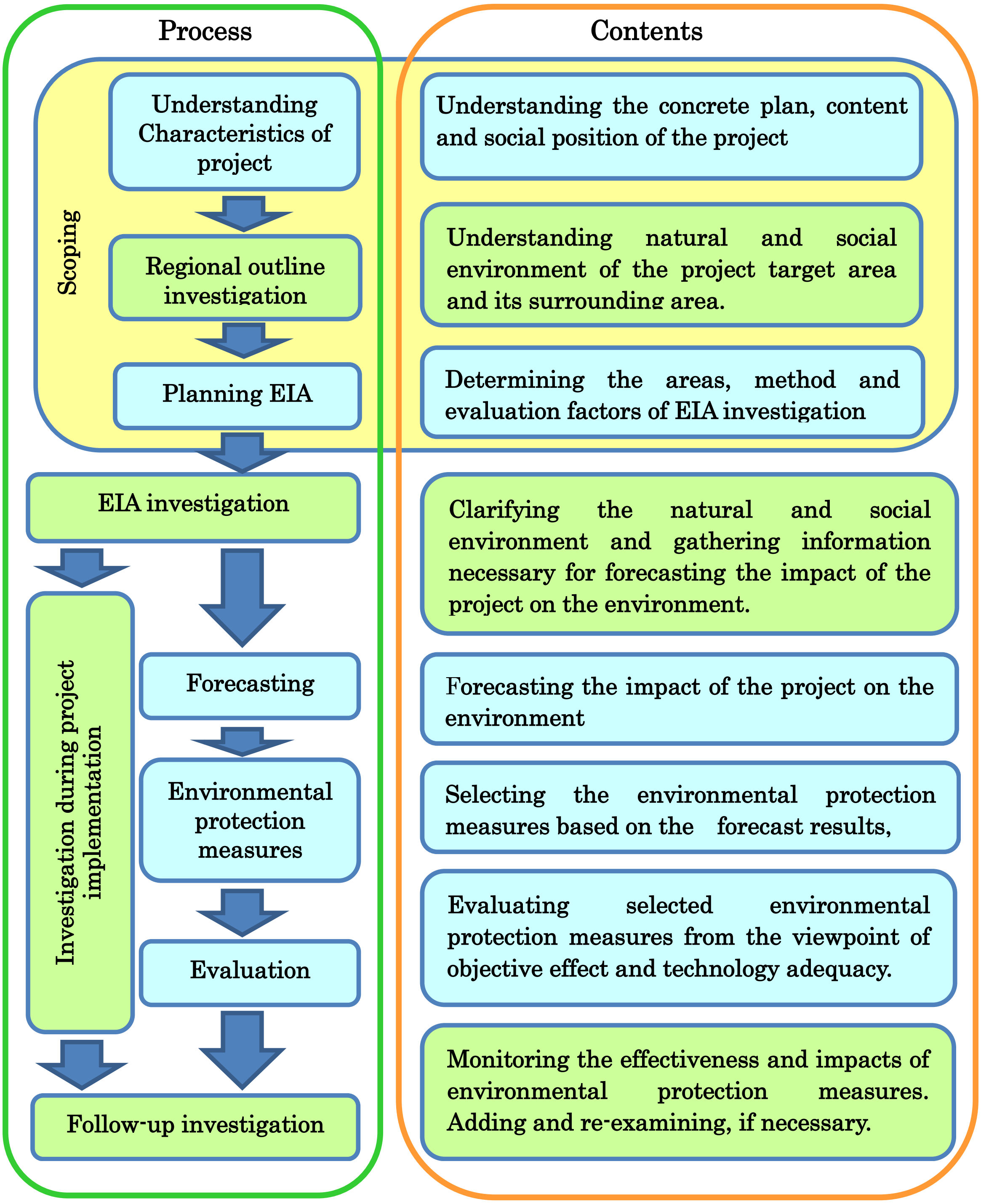


Figure 1.1 Technical Work Process of EIA

(Source: JICA project)

1.2 Proceeding Method of EIA Investigation, Forecast and Evaluation

EIA is a mechanism to make its project acceptable for environmental conservation. Regarding the environmental impact by the implementation of the project, the implementing agency properly conducts investigation, forecasts and evaluates the environment and examines environmental protection measures based on the evaluation of the measures.

The ultimate goal of EIA is "the evaluation of the degree to which environmental impact caused by projects are avoided / reduced by proposed environmental protection measures". At the stage of scoping, it is important to clarify "what to evaluate" first, then select the factors and methods of investigation, forecasting and evaluation. Once a decision is reached, then the EIA investigation proceeds. After the EIA investigation, it is necessary to feed back the information obtained from the investigation to interested parties at any time, review the factors and methods, and proceed with the following steps, which are investigation, forecast and evaluation. When assessing the environmental impact of tunneling to groundwater, it is necessary to take into consideration the characteristics of the groundwater shown in Section 1.3. In addition, compared with other environmental factors, in the case of groundwater, it is often difficult to satisfy quantitative understanding by investigating existing materials in scoping. Therefore, it is also necessary to take into consideration that sufficient field survey is conducted at the investigation stage of regional outline investigation. It is also necessary to pay attention to feedback, review of items and methods, modification of objectives and perspectives at this stage of the EIA.

1.3 Fundamental Characteristics of Groundwater

This guideline provides technical methods in the "EIA of tunnel excavation on the surrounding groundwater environment" and the direct subject of the EIA is the hydrological environment.

1.3.1 Groundwater Flow

Groundwater flows from the higher pressure to the lower pressure and its flow is described by the following Darcy's law.

$$v = \frac{-k\Delta h}{L} = -kI$$

where:

v: volume of water per unit cross-sectional area of a column of permeable materials, expressed as velocity,

Δh: difference in pressure head at the ends of the column,

L: length of flow pass,
k: coefficient of permeability (hydraulic conductivity), a constant based on the character of the material,
I: $=\Delta h/L$, hydraulic gradient (dimensionless).

It is considered that this Darcy's law can also be applied in unsaturated flow.

1.3.2 Classification and Flow by Groundwater Void Structure

Groundwater is classified into three types: pore water, fissure water, and cavern water from the void structure of the ground. Their schematic structures are shown in Figure 1.2. Pore water is groundwater that fills between particles of gravel, sand, silt, weathered rock, and generally spreads horizontally. The more uniform and larger the particle size, the higher the fluidity and the coefficient of permeability increases. Fissure water is water in the fissures or joints or cracks in the rock while cavern water is found in limestone caves caused by corrosion or lava tunnel and so on. These groundwater flows through water veins and storage, and flows are greatly different from pore water. In the fractured ground, the flow of groundwater is localized; but it varies greatly depending on the place and the magnitude of fissures, and their connected state. In fissures that are filled with fine weathered particles, the liquidity is extremely low even in the presence of water.

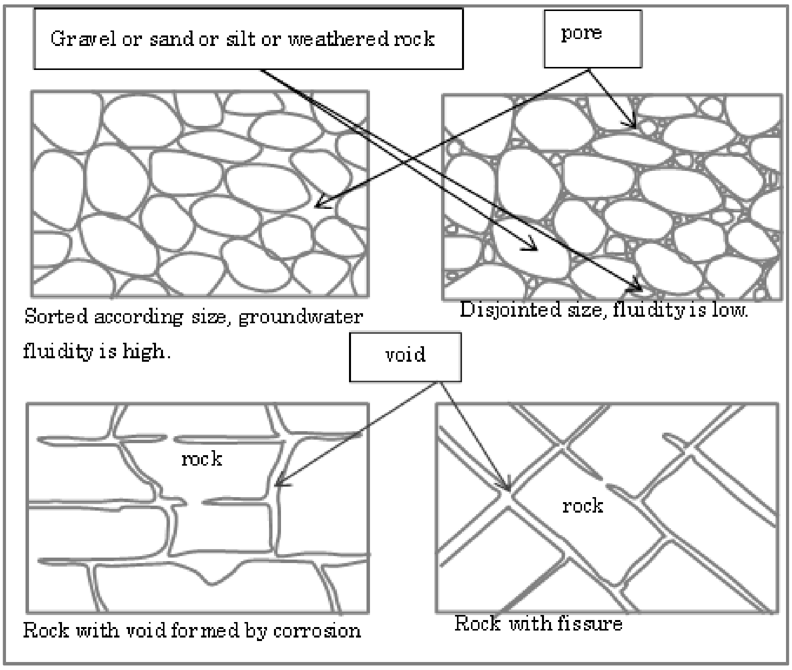


Figure 1.2 Classification of Groundwater by the Void Structure of the Ground

(Source: modified from Groundwater Handbook (in Japanese))

1.3.3 Groundwater and Hydrologic Cycle

Water exists in various areas such as vapor, rain water, river water, lake water, groundwater, sea water and others on the earth. They always circulate by processes such as evapotranspiration, precipitation, flow, infiltration, etc. to other areas as shown in Figure 1.3. Groundwater is one such area. In order to grasp changes in groundwater, not only changes in groundwater but also water balance terms such as rainfall, surface water and water use and their change processes must be analyzed as a "system of the hydrologic cycle".

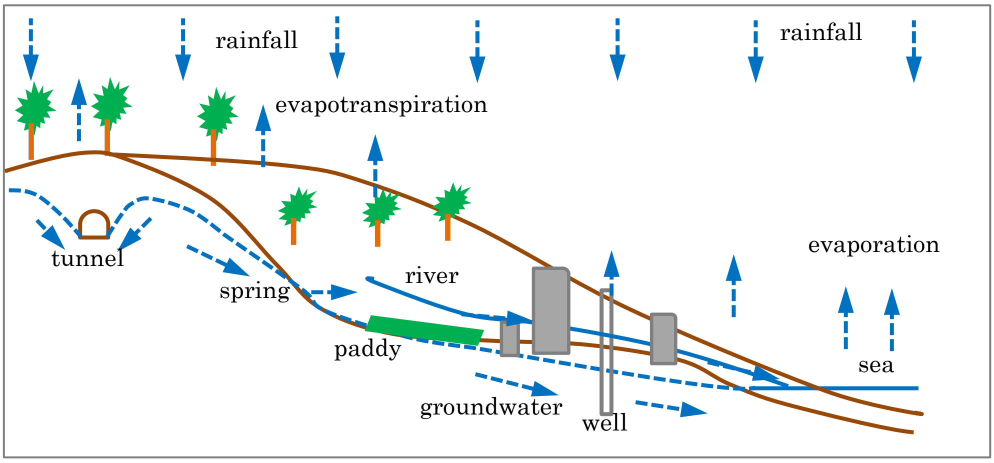


Figure 1.3 Schematic Diagram of Hydrologic Cycle

(Source: JICA project)

1.3.4 Impact of Lowering of Groundwater Level

The excavation of a tunnel may cause the decrease of groundwater, surface water and spring water as a direct impact as shown in Figure 1.4. Chain effects resulting from the decrease may include changes in the hydrologic cycle, accompanying reduction in supply to the outflow area of groundwater, land subsidence, surface displacement, vegetation change, etc. Therefore, in addition to water, it may be necessary for EIA to examine factors that the hydrologic cycle propagates.

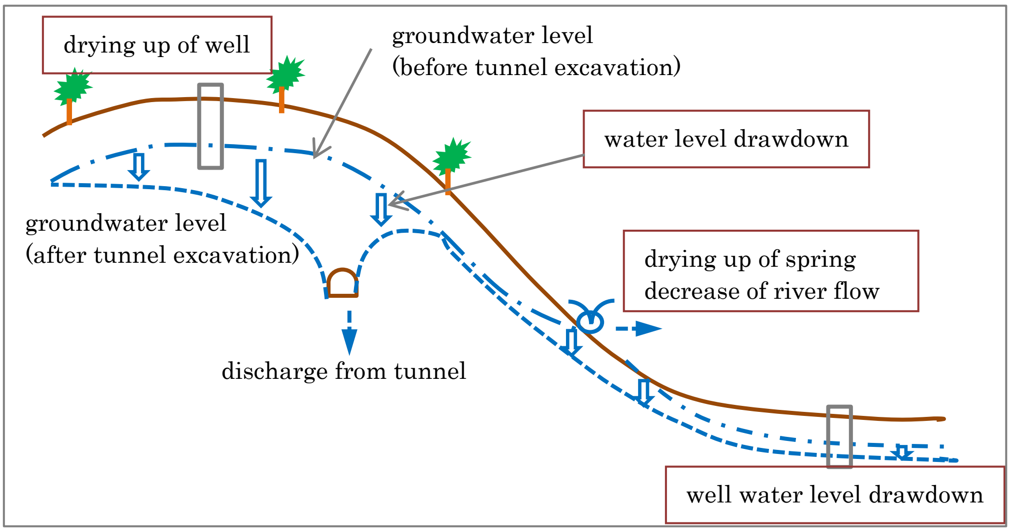


Figure 1.4 Schematic Diagram of Influence on Hydrologic Cycle by Tunnel Excavation

(Source: JICA project)

2 Natural Characteristics of Sri Lanka

2.1 Meteorological Characteristics of Sri Lanka

Sri Lanka is located between 5° 55' to 9° 51' North latitude and between 79° 42' to 81° 53' East longitude with climate characterized as tropical. The ITCZ (inter-tropical convergence zone) dominates the climate in Sri Lanka. The ITCZ is formed near the equator with a high solar radiation as a low-pressure zone in the global circulation and ITCZ generates an ascending air current. The ascending air current divides into southward and northward current in upper atmosphere. Both currents form descending currents and then flow into ITCZ near the earth surface. Air mass from ITCZ completes the circulation. ITCZ moves to north and south according to the change of solar radiation accompanied with earth's revolution. In Sri Lanka, a year is divided into the following four seasons:

a. First Inter-monsoon season (FIM): March to April
b. Southwest Monsoon season (SWM): May to September
c. Second Inter-monsoon season (SIM): October to November
d. Northeast Monsoon season (NEM): December to February

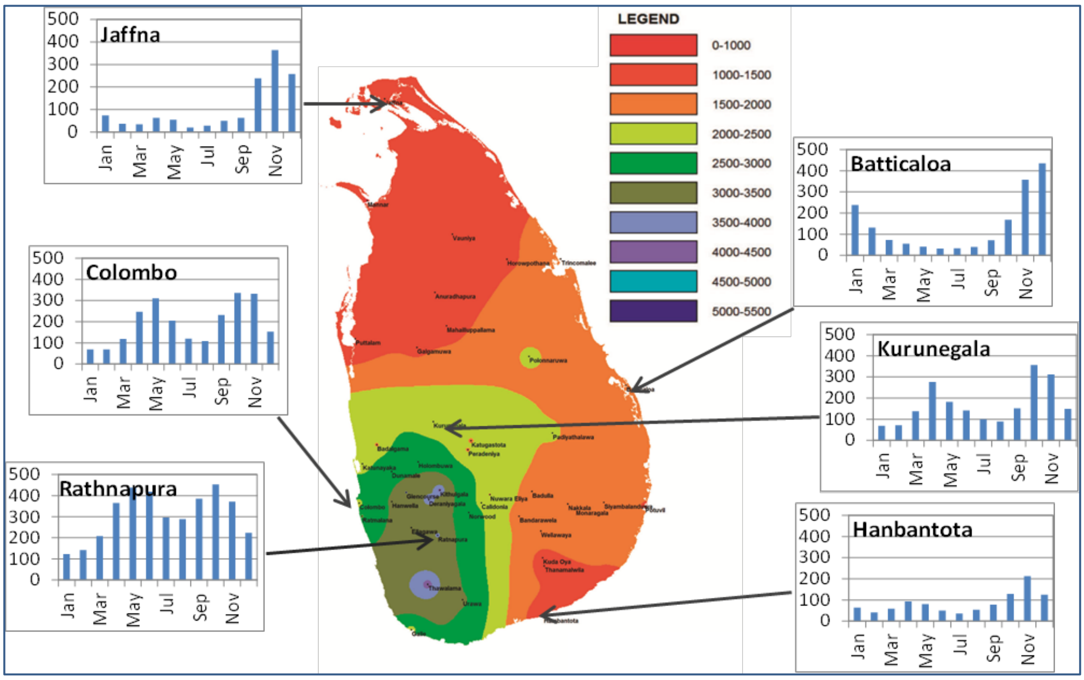


Figure 2.1 Mean Annual Distribution and Monthly Change of Rainfall in Sri Lanka (Oct. 1970-Sep.2015)

(Source: Hydrological Annual 2015/16, Irrigation Department)

These seasons are formed depending on the location of ITCZ. ITCZ is located across or near Sri Lanka during FIM then move north. ITCZ is located north of Sri Lanka during SWM then move south. ITCZ is located across or near Sri Lanka again during SIM then move south. ITCZ is located south of Sri Lanka during NEM then move north. The wind blowing toward ITCZ is monsoon and the name of monsoon period shows its prevailing wind direction.

The annual rainfall distribution and the seasonal change of rainfall at the representative sites in Sri Lanka are shown in Figure 2.1. The average annual rainfall of Sri Lanka is 1,861 mm. The rainfall amount is very varied; the mountainous region in the southwestern part receives the maximum rainfall of more than 5,000 mm but the northwest coastal part receives less than 1,000 mm. Rainfall in the inter-monsoon season occurs due to convection by ascending air current in ITCZ and often accompanied by thunder. As rainfall in the monsoon season is caused by lifting the wet air of the Indian Ocean with the prevailing wind on the slope, more rainfall on the wind oblique slope is much. Therefore, the rainfall is significantly influenced by the terrain and the area; the seasonal change of the rainfall also varies depending on the terrain and the area.

The average annual air temperature in lowlands of Sri Lanka is 27 °C and it drops to 16 °C in Nuwara Eliya with 1,800 m of elevation. The coldest month is January and the hot month is March and April. The annual range of the air temperature is 1 to 5 °C and the temperature change through the year is small. The daily range of air temperature is 5 to 10 ° C and the daily range is larger than the annual range.

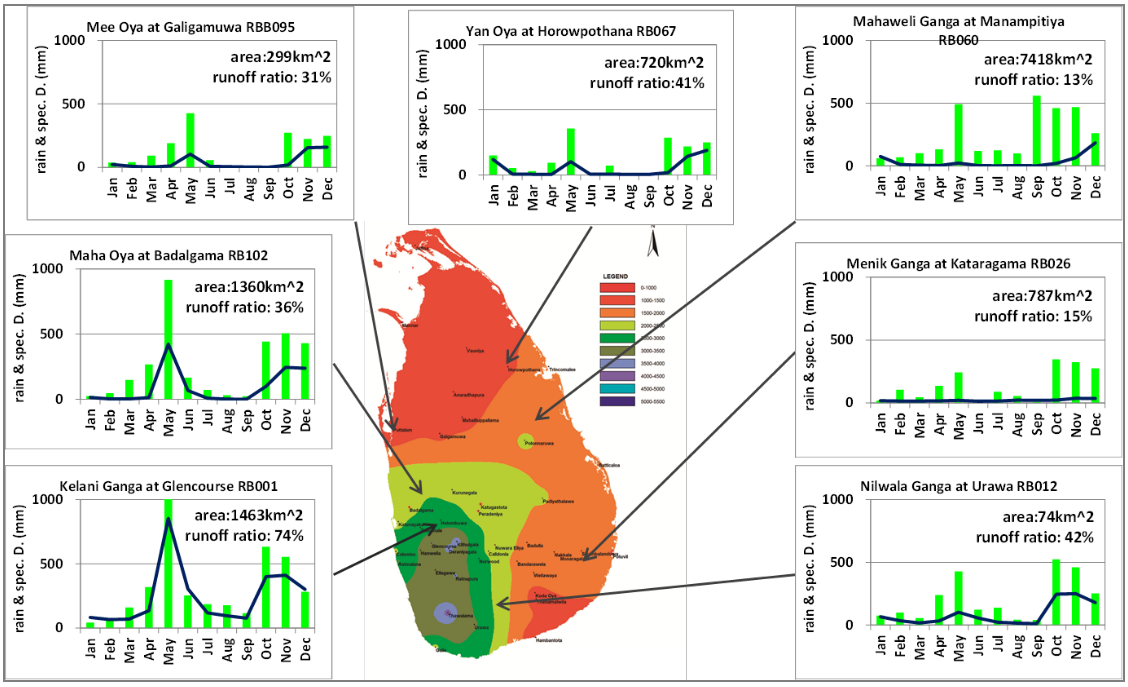


Figure 2.2 Monthly Changes of River Discharge and Rainfall (2015/16) with Annual Distribution of Rainfall (Oct. 1970-Sep.2015)

(Source: Hydrological Annual 2015/16, Irrigation Department)

2.2 Hydrological Characteristics of Sri Lanka

There are 103 rivers in Sri Lanka. Most rivers flow radially from the central mountains. The largest basin is Mahaweli Ganga with a catchment area of 1,946 km^2. In Sri Lanka, more than 90% of the land is underlain by Pre-Cambrian crystalline rocks with low permeability that reduces the infiltration. As a result, a relatively high percentage of rainfall converts to surface water. The runoff ratio (equals runoff / rainfall) exceeds 70% in the wet zone while it is 20 to 30% in the dry zone. The runoff ratio from entire Sri Lanka is estimated to be about 45%.

The monthly discharge and rainfall graph, together with the annual rainfall distribution, are shown in Figure 2.2 to show the seasonal change of discharge. Discharge is indicated by specific discharge (equals discharge / catchment area) to avoid the influence of the size of the basin. It also shows the catchment area and runoff ratio (equals flow rate / rainfall amount). As with rainfall, the discharge is also varied. The figure shows that the discharge changes seasonally according to rainfall and the runoff ratio tends to increase closer to the mountain.

2.3 Hydrogeological Characteristics of Sri Lanka

Seven distinctive types of aquifers have been identified in Sri Lanka (see Figure 2.3). The seven types are: a) shallow karstic limestone aquifers, b) coastal sand aquifers, c) deep confined aquifers, d) laterite aquifers, e) alluvial aquifers, f) shallow regolith aquifers, and g) deep fractured zone aquifers.

Table 2.1 compares the classifications of seven types of aquifers in Sri Lanka and the groundwater classification by the void structure shown in Figure 1.2.

The shallow aquifers, excluding shallow karst aquifers, are pore water among unconsolidated particles such as gravel, sand, silt and weathered rock, and generally spread horizontally. The deep groundwater is mainly fissure water. Fissure water exists in fissures or joints or cracks opened in the hard rock. Although it is not in this classification, there is the possibility that deep cavern water exists. These groundwater flow in the water vein and behave differently from pore water. In general, the flow of deep groundwater is localized in the fractured rock. The flow velocity and the hydraulic gradient of deep groundwater irregularly change depending on the location and size of the fissures and an intermittent groundwater surface is formed.

Investigation of deep groundwater is more difficult than that of shallow groundwater. The reasons are that the deep groundwater exists deep from the earth's surface; one-dimensional form such as water vein exists irregularly.

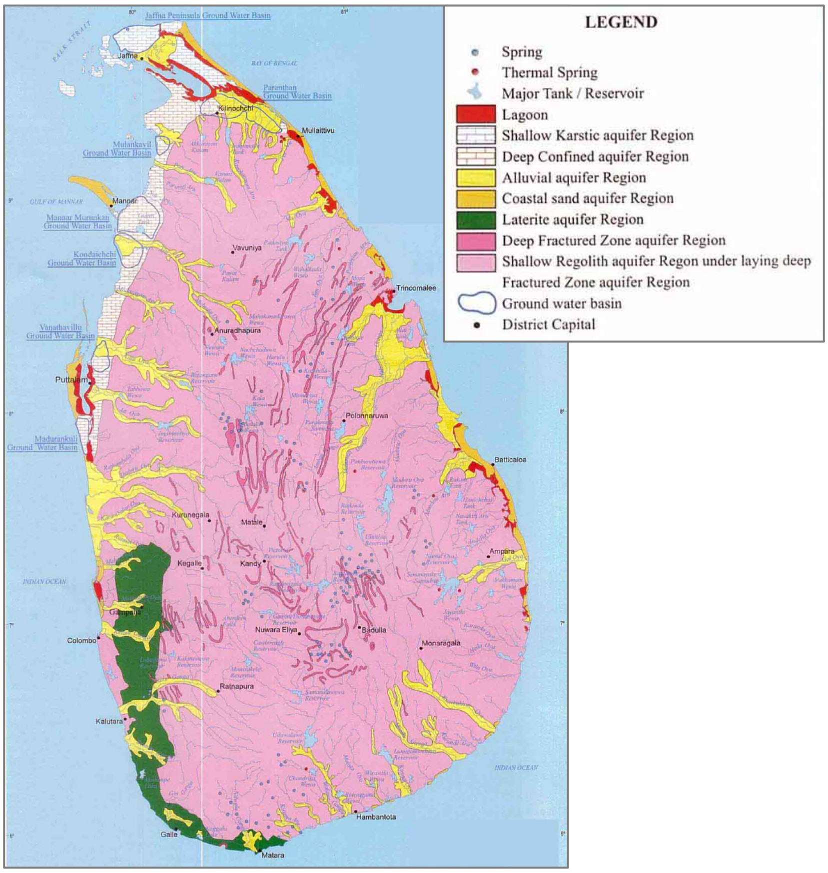


Figure 2.3 Groundwater Aquifer in Sri Lanka

(Source: National Atlas of Sri Lanka second edition, 2007, Survey Department)

Table 2.1 Comparison of Classification of Groundwater by Void Structure and Aquifers of Sri Lanka

(Source: JICA project)

Classification of groundwater by the void structure	Classification of aquifer in Sri Lanka
Pore water	- Alluvial aquifer - Coastal sand aquifer - Laterite aquifer - Shallow regolith aquifer
Fissure water	- Deep confined aquifer - Deep fractured zone aquifer
Cavern water	- (shallow) Karstic aquifer

3 Scoping

3.1 Purpose and Overview of Scoping

Scoping is the examination and decision of investigation / forecast / evaluation method; it is an important process to decide the contents of actual work as shown in Figure 1.1. In scoping, contrary to the actual work process of EIA, consideration is made in the order of 1) examination of evaluation method, 2) examination of forecast method, 3) study of investigation method".

It is important to consider (draft) environmental protection measures to prevent repeat of work resulting from inadequate survey and selection of inappropriate forecast method, and to evaluate the adequacy, specificity and objectivity of environmental protection measures. Once the project plan is finalized, it may be difficult to formulate appropriate environmental protection measures. Therefore, to implement the appropriate EIA, it is necessary to organize policies of environmental protection measures from the early stage of the project plan and to concretize the content / method according to the stage of progress of the project plan.

3.2 Understanding Project Characteristics

The following items are identified to describe project characteristics related to groundwater. It is sometimes difficult to clarify the details, but it is possible to identify the contents by referring to similar cases during the scoping when the content of the project plan is not established.

a. Items related to implementation of construction
- Construction materials, construction method, and construction duration
- Location and extent of construction
- Measures to prevent water pollution during construction

b. Items related to the existence and service of facilities
- Content, location, and scale of facilities
- Terms of service of facilities, plan and policy concerning operation
- Amount and type of intake by facilities and discharge / drainage from facilities, water intake / discharge drainage position
- Water environmental change accompanying the use of facilities

3.3 Regional Outline Investigation

The regional outline investigation is an important fundamental investigation to understand the characteristics of the natural and social environment of the target area. It is conducted to determine the factors and methods of investigation, forecasting and evaluation for appropriate EIA based on understanding the characteristics of tunnel excavation.

3.3.1 Factors of Outline Regional Investigation

An outline regional investigation consists of the investigation of existing data and information obtained from experts and residents. The assumed factors of the outline investigation are shown in Table 3.1. It is not necessary to investigate all the factors listed in this table. However, it may be necessary to add investigation factors as needed. Basically, it is a document survey to grasp regional characteristics, but if it is deemed necessary, a sufficient field survey should be considered and carried out.

Table 3.1 Factors of Outline Regional Investigation on Groundwater
(Source: JICA by the project)

Investigation factors		Contents
Natural environment	Hydrogeology (groundwater)	Classification, water level, water flow, catchment area, water quality etc. (groundwater storage / flow situation)
	Surface water, spring	Water level, flow, water quality etc.
	Soil, ground	Vegetation, covering condition, permeability etc.
	Terrain, geology	Topographic map, geological map, hydrogeological map, aerial photograph, satellite image etc.
	Meteorology	Rainfall amount, air temperature, evapotranspiration amount etc.
	Other	Factors affected by hydrological cycle (animal and plant distribution, ecosystem)
social environment	Population, industry	Residential area, industries affecting groundwater etc.
	Land use	Land utilization related to vegetation and land cover etc.
	Groundwater use	Domestic water, agricultural water, industrial water etc.
	Surface water use	Intake water volume of intake facility etc.
	Facilities easy to be affected	Existing water source wells, existing water intake facilities, etc.
	Laws and regulations	Laws and regulations related to groundwater and surface water etc.
	Others	Artificial facilities related to hydrologic cycle, etc. (existing underground structure etc.)

When doing tunneling work in deep hard rocks, the survey should address the presence of fissure water and cavern water. Difficulties are expected in the investigation, and the method of EIA investigation is different from that for pore water. If it is judged that there is a possibility of deep groundwater from the document survey of topography and geology, it is better to carry out geological field survey to locate joints, faults and fracture zones to evaluate water-tightness and potentiality of a gush groundwater together with the stability of rock mass.

3.3.2 Area of Outline Regional Investigation

The coverage of the outline regional investigation is "a range where the state of the environmental impact by a certain degree or a range where the environment is directly subject to modification by tunnel excavation and their surrounding area"; it varies widely from factor to factor.

In addition to the system of the hydrologic cycle such as rainfall, evapotranspiration, water use, surface water, etc., there are "terrain and geology" that determine the storage of groundwater. In addition, groundwater storage and flow are regulated by conditions such as slope and permeability of the strata, crack situation of the rock, geological structure, etc. Therefore, considering the hydrologic cycle and the terrain and geology, it is necessary to set the coverage of the outline regional investigation.

3.3.3 Period of Collecting Data in Outline Regional Investigation

It is desirable to acquire long-term data for more than one year because the fluctuation cycle of rainfall, level of surface water and groundwater occurs within one year with seasonal fluctuation. It is also necessary to verify the seasonal fluctuation during the year, the wet season and dry season. As mentioned in Sections 2.1 and 2.2, weather and hydrology in Sri Lanka vary with time and location. With that in mind, it is desirable to investigate near the target area and refer to long-term data.

3.4 Planning of EIA Investigation on Groundwater

The factors of EIA are set based on the relationship between the impact factors identified from the project characteristics and the environmental factors identified from the characteristics of the project implementation area and the area characteristics around the project area. According to this guideline, because the project is limited to tunnels and groundwater, groundwater level lowering due to discharge to tunnel is assumed. However, it is necessary to consider that the impact appears differently depending on where these impact factors occur in the hydrologic cycle.

3.4.1 Determination of Environmental Factors for Investigation, Forecast and Evaluation

During scoping, investigation methods that can forecast and evaluate the impact of the project works are selected based on the result of examination of the influence of tunneling work on groundwater and the results of the regional survey. It is also necessary to select investigation methods keeping in mind that the factors constituting the hydrologic cycle are not independent of each other but are closely related to each other in a system. Methods for possible investigating environmental factors are shown in Section 4.4.

3.4.2 Setting of Investigation Area

It is necessary to identify the investigation area, which could be decided based on the regional outline investigation. It usually encompasses the project implementation area and its surrounding area according to the characteristics of the project and the regional characteristics including the terrain and geological conditions. The investigation area is studied to verify detailed information on the hydrological environment, which was initially obtained through document review and field investigation. There is an example that the investigation area of a mountain tunnel excavation is the expanse where basins overlap within 500 m on both sides of the tunnel (Technical guidance of EIA, 2017, p.237). However, it is prudent to decide on the investigation area after considering the basin of surface water and groundwater as a system of the hydrologic cycle. In some cases, it is also desirable to investigate other implementation cases under similar conditions.

3.4.3 Attention in Investigation Planning

At the scoping stage, the consideration is made in the order of 1) evaluation method, 2) forecast method, 3) investigation method" which is opposite to the order of actual work process of EIA. It is also important to consider environmental protection measures to prevent repeat work resulting from inadequate investigations and selection of inappropriate forecasting methods, and to judge the validity, concreteness and objectivity of environmental protection measures.

In the case of insufficient results from the regional outline investigation, it is advisable to add thorough site surveys and to ensure thorough selection of factors and methods of investigation, forecasting and evaluation.

4 EIA Investigation Related to Groundwater

The purpose of the EIA investigation is to gather information that could not be clarified in the regional outline investigation. It is also needed to describe the current situation of the target area in a more detailed and quantitative manner as much as possible; acquire necessary information for forecast of possible impacts from tunneling works on groundwater, identity environmental conservation measures, and evaluation.

4.1 Investigation Factors

The investigation factors that are supposed to be used to identify "impacts on groundwater by tunnel drilling" are shown in Table 4.1. These factors vary depending on the scoping results. Even using the same factors as in the regional investigation, the investigation method is different, and the methods of investigating hydrological geology are particularly different. Specific investigation methods are shown in Section 4.4.

Table 4.1 Factors, Objects and Method of EIA Investigation on Groundwater
(Source: JICA project)

Factors	Objects	Method
Land use, land cover	Land use, land cover, vegetation, animals and plants	Interpretation (topographic map, satellite image), site survey
Soil	Soil distribution, soil moisture, existing structure	Site survey, measurement
Geology	Geological structure	Interpretation (topographic map, geological map, satellite image), site survey
Meteorology	Rainfall, evapotranspiration	Data collection, meteorological observation
Surface water	River discharge, water usage, water quality	Data collection, hydrological observation, water quality analysis
Spring	Spring discharge, water usage, water quality	Data collection, hydrological observation, water quality analysis
Well	Water level, water usage, water quality	Data collection, observation
Hydrogeology	Structure and properties of aquifer	Seismic prospecting, Electric exploration, boring, electric logging, pumping test, observation of groundwater level

4.2 Setting of Investigation Area

The investigation area includes the project implementation area and its surrounding area according to the characteristics of the project and the regional characteristics including the terrain and geological conditions. There is an example that the investigation range of a mountain tunnel excavation is the areal extent where basins overlap within 500 m on both sides of the tunnel (Technical guidance of EIA, 2017, p.237); it is necessary to set the investigation boundaries after considering the basin of surface water and groundwater as a system of the hydrologic cycle. The investigation area is studied to grasp detailed information on the hydrologic cycle through document review and field investigation. The investigation method is decided based on the regional outline investigation. In some cases, it is also desirable to investigate other implementation cases under similar conditions.

4.3 Considerations of EIA Investigation

Field survey is the main investigation method in the EIA investigation. Prior to any field survey, the residents living in the field are gathered in a meeting to seek their cooperation in the study. The details of the project and the purpose of the survey are explained to the residents to have a common understanding of the project, in this case tunneling work as well as the purpose of the field survey. It is explained to the residents that the field survey will include observing the water level of wells owned or used by residents. It is further explained that the results of this survey will contribute to the setting of environmental impact protection measures. Therefore, the cooperation of residents is indispensable and should be sought.

EIA investigation is conducted by several experts and it is important to share information among experts. Collected or obtained data must be organized properly and shared among experts. In particular, sharing is important in case of new or unexpected findings because there is a possibility that it is necessary to change the investigation method and place of investigation.

4.4 Land use and Land Cover

4.4.1 Investigation of Existing Information

A land use map, vegetation map, aerial photograph, etc. are collected and studied. Land use, the land covering situation and vegetation are clarified using map interpretation and vegetation cover identification. If there is any future land use plan, the plan is also considered. An aerial photograph is a powerful tool to use in areas where existing information is poor, because vegetation, land use, and subtle relief of terrain can be read from it.

4.4.2 Site Investigation

A site investigation is conducted. The results of the site investigation combined with existing information are used to prepare a land use map and vegetation cover map.

4.4.3 Investigation of Existing Information

Meteorological data on air temperature, humidity, solar radiation (sunshine hours) and wind speed are collected for calculating the amounts of rainfall and evapotranspiration in the investigation target area and its upstream catchment area. If there are no observation data in the target area, data at observation stations adjacent to the area are collected. Long-term daily data is desirable. At least the data of a few years are necessary.

4.5 Soil

The lowering of the groundwater level may cause ground subsidence, surface mutation and changes to plants and ecosystems.

4.5.1 Investigation of Existing Information

Soil distribution is clarified by collecting existing soil maps and other materials in the investigation target area.

4.5.2 Site Investigation

Soil moisture is measured during the dry season, if impacts on plants and ecosystems are forecasted. Also, if terrain changes such as subsidence are expected, investigation of existing structures is conducted.

4.6 Geology

4.6.1 Investigation of Existing Information

The existing geological map, surface geological map and hydrogeological map are collected. Documents and papers published around the target area, the geological log from drilling and soil test results are also obtained. These existing maps and documents are reviewed.

4.6.2 Site Investigation

Field investigation will be conducted on outcrops within the investigation target area. The following information will be clarified: a) state of sediment, b) rock quality, c) stratification / schistosity, d) strike / inclination, e) joint, fissure and crack, f) fault, folding structure, g) shape and particle size distribution of soil, and h) hardness, solidification, weathering and alteration of rock, etc. The geological structure is verified from the results of the site investigation and geological map study. Geological surveys targeting joints, faults and identification of fracture zones which lead to deep groundwater especially need to be done.

4.7 Meteorology

Rainfall and evapotranspiration are quantitatively investigated and analyzed from the viewpoint of the hydrologic cycle as well as groundwater recharge in the target area. As mentioned in Section 2.1, Meteorological environment in Sri Lanka varies with time and location. Therefore, particular attention should be paid to it and investigate in the vicinity of the target area.

4.7.1 Investigation of Existing Information

Meteorological data on temperature, humidity, solar radiation (sunshine) and wind speed are collected for calculating precipitation amount, evaporation amount, and evapotranspiration amount in the target area and its upstream area. Long-term data is desirable. At least 10 years' data are necessary.

4.7.2 Rainfall

If there are no rain observation stations in the target area or no observation stations at representative locations, new continuous rain gauges are installed, and rainfall observation starts at the representative locations.

4.7.3 Evapotranspiration

It is common to calculate the potential evapotranspiration amount using pan evaporation data and pan coefficient or the Penman or Thornthwaite method.

However, since the possible evapotranspiration amount is larger than the actual evapotranspiration amount, the difference becomes large especially in the dry season. Therefore, it is better to calculate the actual evapotranspiration using the complementary method (Morton, 1983)[2]. The complementary method can be calculated by $E = 2\,ETW - Ep$. ETW is the potential evapotranspiration in a dry environment and can be calculated by the method of Szilagyi and Jozsa (2008)[3]. Ep is Penman's potential evapotranspiration.

4.8 Surface Water

Investigation items for surface water include discharge, water quality, and water use.

2 F. I. Morton (1983) Operational Estimates of areal evapotranspiration and their significance to the science and practice of hydrology, J. Hydrology, vol.66, 1-76.

3 J. Szilagyi and J. Jozsa (2008) New findings about the complementary relationship-based evaporation estimation methods. J. Hydrology, vol.354, 171-186

4.8.1 Hydrological Investigation

It is preferable that there is discharge data for each catchment area within the investigation target area. Based on the terrain and geological conditions, the groundwater condition, the distance from the location where the possible terrain change occurs possibly caused by the project, etc., the hydrological stations are set in several drainage basins as necessary. Data of at least a year are required and long-term data are desirable. As mentioned in Section 2.2, hydrological environment in Sri Lanka varies with time and location; it is important to always take these variations into consideration during the EIA study.

(1) Investigation of Existing Information

Data on water level and flow at hydrological observation stations in the investigation target area are collected and organized. If there is water level record without flow (volume), it is necessary to convert the water level to flow by using a stage-flow curve. A stage-flow curve can be created by performing discharge measurement or indirect measurement (Tate Galrymple, M. A. Benson, 1989)[4] using the investigation results at the station.

(2) Discharge Measurement

If there is no existing observation station in the investigation target area, discharge measurement must be started at appropriate location. Monthly discharge measurements are preferable, or measurements should be made four times in a year in the least, including the wet and dry seasons. If numerical analysis is planned at the forecast stage, more detailed data is required. Therefore, it is necessary to conduct hydrological measurements including continuous water level observation and discharge measurement to create a stage-flow curve at the representative point.

4.8.2 Water Use

If surface water is used, information such as water use locations, water use amount, and purposes of use are collected. In case environmental water or water rights is set by government or local government, it is necessary to collect that information as well.

4.8.3 Water Quality

While groundwater is flowing or stored in the earth after precipitation infiltrates through the

[4] Tate Galrymple, M. A. Benson (1989): Measurement of peak discharge by the slope area method, Techniques of water-resources investigations of the United States Geological Investigation, Book 3, ChapterA2, U. S. Geological Investigation.

earth's surface, chemical reactions add and change the chemical components of the groundwater. Therefore, it is possible to understand the flow system by investigating the main dissolved components. The parameters of water quality analysis are water temperature, pH, electrical conductivity, Na, K, Mg, Ca, Cl, NO_3, SO_4, HCO_3, and Fe. The flow system can be understood by creating a hexa-diagram and trilinear diagram based on analysis results. Water, not in the wet season but in the dry season, is analyzed because water just infiltrating from the earth's surface also flows out into rivers during the wet season.

4.9 Spring

The investigation of springs is very important because of the following reasons: 1) spring water is the outcrop of the groundwater, 2) the presence of an impermeable layer is expected in the bottom of the water source, and 3) it is also often used as domestic or agricultural water.

4.9.1 Investigation of Existing Information

Existing information on the location, flow rate, water quality and other characteristics of spring water is collected.

4.9.2 Site Investigation

The locations of springs are investigated based on existing materials and information from interviews and investigation of spring water. Investigation is conducted at representative locations. Useful information can be obtained through interviews of residents because some springs are used as domestic or agricultural water or water sources of small rivers. Observation parameters and periods are in accordance with surface water. Monthly discharge measurements are preferable, or measurements should be made four times in a year in the least, including the wet and dry seasons. Water quality is sampled and analyzed during the dry season. The amounts of water use are clarified by the investigation of the usage situation.

4.10 Well

4.10.1 Investigation of Existing Information

The following information of the existing wells is collected: location, structure, aquifer structure, borehole log, water quality, time series data of water level, and yields.

4.10.2 Site Investigation

The following information on the wells is collected: wells used for water level observation, domestic water, agricultural water, and industrial water, etc. Data are collected and organized through on-site investigation and questioning to well owners. The data include location, structure, aquifer structure, borehole log, water quality, time series data of water level, and yields. Water sampling and analysis are the same as those for surface water. The periodic measurement of water level, yield and water quality is started for wells considered to be important.

4.11 Hydrogeology

4.11.1 Investigation of Existing Information

A geographical map, geological map, hydrological map, spring water information etc. are collected and geological sections and groundwater level distribution maps are created. The collected information is organized and the outline of the aquifer, such as the size and depth, is clarified.

4.11.2 Seismic Exploration

It is possible to estimate the degree of consolidation, weathering degree, alteration degree, cracks from the comparison between seismic exploration by the refraction method and elastic wave speed of fresh rock samples. In particular, it is possible to obtain useful information for aquifer structure analysis of fissure water through seismic exploration. However, it is not an appropriate investigation method in complicated geological structures, so it is necessary to use it in combination with other methods.

4.11.3 Electric Sounding

Electric sounding is a method of investigating geology by artificially run electricity underground. The general method is a resistivity method and the apparent resistivity of geologic formation is measured. Rock harder than soft rock, dry rock than watery rock, sandy soil than the clayey soil have a higher resistivity, so the aquifer can be distinguished.

4.11.4 Boring Investigation

It is possible to clarify the structure of the aquifer from changes in total water volume, leakage volume and the change of water level during boring excavation. These records are shown in the borehole log and in the relation diagram between the drilling speed and the groundwater level. By the observation of the boring core, the permeability coefficient and its thickness are classified. In the case of soil, the particle size distribution, the uniformity coefficient, the porosity, etc. are arranged in a geological log. In the case of rocks, RQD

(Rock Quality Designation, the ratio of the total length of 10 cm or more cores with the drilling length) is also arranged in the geological log. The smaller the RQD, the more cracks are found, and it can be said as potential water-containing ground. However, it is wrong to judge water permeability only by RQD. It should be judged in conjunction with investigations such as logging and pumping tests.

After completion of the boring investigation, drilled wells considered important are used as groundwater observation wells. Water quality is analyzed in the dry season.

4.11.5 Borehole Logging

Velocity logging, electrical logging, temperature logging and observation by borehole camera are performed to estimate the aquifer position and water permeability. These results are also organized in the borehole log.

4.11.6 Capacity Test of Aquifer

The amount and fluidity of groundwater are generally evaluated by the transmissivity and the storage coefficient. These numerical values can be obtained by the following method.

(1) An Estimation Method by Water Level Change in a Well

Approximate water permeability around the shallow well can be obtained as the specific capacity (Q / S), where S is the water level drop and Q is the constant yield of the well. This is the same unit as transmissivity (T). The relation between Q / S and T can be obtained beforehand and T can be estimated from the value of Q / S.

(2) Pumping Test

Transmissivity and the storage coefficient can be calculated by the measurement of the water level drop during the pumping stage and the water level recovery stage after the stop and by using the formula of Jacob, Theis or Nomitsu. If it is necessary to know the capacity of a well, the following method is taken; a) measuring the drawdown (Sn) in equilibrium stage after several stages of pumping (Qn), b) obtaining aquifer loss (virtual drawdown B when Q = 0), c) plotting the logarithms of Qn and (Sn / Qn - B), d) determining the critical yield (Qn) at the break point where the slope is 1 or more, e) determining transmissivity and the storage coefficient by conducting the pumping test on appropriate yield based on Qn.

(3) Pressure Test of Water Upwelling from Bottom-hole

Transmissivity is obtained by the following method: a) packer is installed at target depth in the borehole, b) opening part of the packer after restoring near groundwater conditions before drilling, and c) measure the rising speed of water from the hole bottom.

(4) Measurement of Micro Flow Velocity

Transmissivity for each depth are obtained by substituting measurement values over the entire length of the borehole under the condition of the natural water level and the artificial water level (by pumping or pouring) into the following formula after the installation of a micro-current meter.

$\mathrm{K} = Qt/(2\pi\Delta p)ln(R/r)$,

where

Δp: water head difference between natural and artificial water levels

Q: increase in flow rate per unit section

R: influence range

r: radius of borehole

(5) Pouring Water Test

Transmissivity is obtained from the relation of the pressure, flow rate, time and head of water while injecting water into the borehole. The Lugeon test is a standardized method and conducted as follows: a) setting a packer at the position of effective length L = 5 m from the hole bottom, b) pouring water under pressure P = 10 kgf/cm^2 as a standard, c) Q l / min is the steady water pouring rate, d) Lugeon value (Lu) is obtained by $\mathrm{Lu} = (10/P)/(Q/L)$.

1 Lu is converted to roughly 10^{-5} cm / sec. This method is often used as a simple evaluating method of the grouting effect.

(6) Tracer Method

It is a method to measure the time and concentration change that chemicals reach at an observation point by inputting chemicals which are difficult to react with groundwater, detectable even in dilute concentration and which do not interfere with water quality standards. The following chemicals can be used; saltwater, fluorescent dye, ammonium phosphate, and isotope. There is also a method of using radioactive isotopes (tritium, carbon, radon, etc.) mixed in groundwater.

(7) Indoor Test

The approximate effective porosity and permeability coefficient can be estimated from the measurement of the true specific gravity, the weight of unit volume and particle size distribution of the sampled unconsolidated ground soil particles.

(8) Measurement of Soil Permeability

The permeability of surface soil is an important indicator for judging the ability of soil to recharge groundwater from the viewpoint of water balance. It is also an important indicator to estimate the necessary amount of irrigation in the paddy field, which is important in the field of agriculture.

- Infiltration test

The rate at which the precipitation and irrigation water infiltrates the soil is called the infiltration rate. This rate is initially large and gradually decreases over time and the maximum value is called infiltration capacity. The infiltration rate is measured with a cylindrical infiltrometer.

- Measurement of water requirement rate

The water requirement rate is an indicator showing the amount of water consumed in paddy fields in terms of water depth per day. This is frequently used for calculating the amount of water required for paddy fields.

This is the sum of the amount of evapotranspiration and infiltration and it also depends on the soil and topography of the paddy field, the state of groundwater level and the growing condition of paddy rice. As for the water requirement rate as a water supply plan, it is sufficient to know the amount of water (cm) during the ploughing season and the water requirement rate (cm / day) in the normal water use stage.

- Measurement of pF value

The pF value is an indicator of soil moisture condition, which is the logarithm of the unit water column height (cm) necessary for removing the water bonding from the soil particles. Since the soil after the precipitation is saturated with all kinds of water ranging from gravity water to moisture absorbing water, the pF value is low, but when the fine weather continues, the gravity water disappears, and the pF value rises to roughly 3. The pF value of the soil water that can be absorbed by plants is in the range of 1.8 to 3.8 and it is said that it is necessary to irrigate when the pF value is more than 3.6. It is possible to evaluate the influence of the excavation work by knowing the change in the pF value beforehand in relation to the precipitation and comparing it with the fluctuation trend after the tunnel construction.

4.11.7 Points to Note on Hydrogeological Investigation

(1) Difficulty of Hydrological Geological Survey

It is difficult to acquire accurate and high-resolution hydrogeological data. Since the subject of investigation is underground, it cannot be seen and its investigation is from a remote place. Seismic prospecting, electrical exploration and boring investigation are useful methods to obtain hydrogeological information. In the seismic exploration and the electrical exploration, the data obtained through the medium from a distance is analyzed, and the average elastic wave velocity and the specific resistance value of a certain volume are obtained. Therefore, it is difficult to obtain high resolution results. High resolution results are obtained in the boring investigation, logging and aquifer tests. Although these provide high resolution information, it is difficult to estimate the regional extent of them. If information at that high resolution is needed, the number of boring will increase and cost will become high. By compiling the results of geological survey, seismic prospecting, electrical exploration, etc. and determining the location of the boring, it is possible to efficiently advance hydrological geological survey.

(2) Difficulty of Investigation Method due to Difference in Aquifer

Groundwater is classified into pore water between particles of rocks, sand, clay, weathered rocks, fissure water in rock masses and cavern water. The schematic diagram of groundwater classification is shown in Figure 1.2. Since the pore water has thickness, and spread in the lateral direction, it is not so difficult to know the location and structure. On the other hand, fissure or cavern water in the rock is present not in a two-dimensional spread, and are distributed nearly randomly, so it is not easy to know the location. Also, even if you know the existence of water in the hard rock, it is difficult to know if the water will flow. If the crack is hollow, water will flow, but if it is a crack filled with fine clay, little water will flow. In order to know the characteristics of fissure or cavern water, it is necessary to rely on boring investigation. In the case where the existence of fissure water is predicted, it is necessary to compile the geological survey results such as location of faults and lineament, the seismic prospecting results, the electric exploration results and so on. The position of the boring is decided carefully and the hydrological geological survey advances further.

(3) Processing of Groundwater Data

The basin, depth and flow characteristics of groundwater are clarified by combining the information of topography, geology, surface water, spring, wells and hydrogeological data. Long-term and seasonal fluctuations of groundwater are also verified. If data is insufficient from the viewpoint of forecast and evaluation, it is necessary to drill new boreholes and acquire additional information.

5 Impact Forecast on Groundwater

5.1 Concept of Impact Forecast

It is important to consider groundwater as an element of the hydrological system in the target area, rather than individually handling elements such as surface water, groundwater, soil etc. Therefore, it is necessary to pay attention to the following points and proceed with the consideration while forecasting impact; always keeping in mind how the effect of tunnel excavation works on the hydrological system and examining the detailed impact by feeding the results of the effect back to the groundwater.

When the tunnel excavation begins, the groundwater above the tunnel starts discharging into the tunnel and the groundwater level above the tunnel starts declining. Along with this, the water level of wells declines, and the discharge of spring water decreases in the influence area. It takes some time for the groundwater above and surrounding area to reach an equilibrium state. Since the influence on the surrounding environment is considered to be the largest after the groundwater reaches equilibrium, this guideline covers the environment after the equilibrium state.

5.2 Forecasting Area

It is necessary to set a range that fully covers the impact of the project, including the range to be affected by the project as well as the surrounding range where the influence does not occur as the comparative area. Since it is necessary to clarify the state of surface water and groundwater etc. in the hydrological cycle system, it is necessary to set the boundary of the forecasting area by paying attention not only to the topographical drainage basin but also the catchment area of the groundwater. If the groundwater flow changes in the groundwater recharge area, the influence may also affect the groundwater outflow area, so the forecasting area needs to be set to encompass both.

5.3 Target Time of Forecast

It takes a long time for surrounding groundwater to reach equilibrium in some cases. Considering these cases, it is necessary to set the target time of the forecast. It is also necessary to consider the forecast in the dry season when the influence on groundwater becomes greater.

5.4 Forecasting Method

Careful consideration is needed to choose the forecasting method because of the required condition, the accuracy of the result obtained, the application conditions, and so on are greatly varied. The forecasting methods are as follows:

- Forecasting by using existing similar cases,
- Simplified calculation by using hydraulic formulae,
- Takahashi's forecast method,
- Hydrologic analysis by using the Tank Model,
- Numerical analysis by groundwater simulation, and
- Model experiments.

5.4.1 Forecasting by Using Existing Similar Case

The forecasting by using existing similar cases is a method of collecting as many similar examples as possible, arranging and analyzing them, and forecasting the groundwater discharge into the target tunnel.

This method gives the amount of discharge simply by the length of the tunnel. The estimates should be treated as a mere reference because the soil covering and individual features are not taken into consideration.

In Sri Lanka, data accumulation is not enough, and this method cannot be made. We would like to make efforts to accumulate data and compilation.

The example of Japan is shown below for reference only. This cannot be applied in Sri Lanka because the environment is different from that of Sri Lanka.

An example in Japan summarizing the results of 273 railway tunnels[5] is shown in the following equation.

$$Q = 0.1L^2,$$

where Q : equilibrium state discharge (m^3/min),

L: length of tunnel (km).

[5] Study on discharge and drought associated with tunnel excavation, vol.2, Japan Tunneling Association. (in Japanese)

However, the data variation is large and the correlation coefficient is as low as 0.53.

The equation for big discharge is shown below.

$$Q = 4L^{0.32},$$

The incidence rate of the specific discharge into the tunnel (the amount of discharge per unit length of tunnel) of all rock materials is shown in Table 5.1.

Table 5.1 Incidence Rate of Specific Discharge into Tunnel
(Source: Study on discharge and drought associated with tunnel excavation, vol.2, Japan Tunneling Association. (in Japanese))

Specific discharge (m^3 / min / km)	Percentage (%)
0.25 or less	53
0.5 or less	73
1.0 or less	82
1.5 or less	91

The discharge into the tunnel of more than 80% is 1.0 (m^3 / min / km) but 9% is more than 1.5 (m^3 / min / km).

The amount of spring water by geology is shown in Table 5.2.

Table 5.2 Specific Discharge into Tunnel by Geology
(unit: m^3 / min / km, the value in brackets indicates fractured rock)
(Source: Study on discharge and drought associated with tunnel excavation, vol.2, Japan Tunneling Association. (in Japanese))

Geology		Range of specific discharge	Average of specific discharge
Volcanic rock, volcanic crash rock		0.035~0.9 (0.85~10.0)	0.30 (3.71)
Plutonic rock including gneiss)		0.018~0.84 (0.17~3.80)	0.20 (1.38)
Palaeozoic, Mesozoic		0.0~0.95 (0.10~4.50)	0.17 (0.79)
Tertiary ~ Pleistocene	Sand and gravel	0.02~3.6	0.87
	Sandstone, Shale, Tuff	0.014~0.95	0.25
	Mudstone	0.0~0.26	0.07

5.4.2 Simplified Calculation by Using Hydraulic Formulae

There are various types of discharge formulas into tunnels based on the hydraulic formulae, but most are to estimate the discharge volume by inputting the range of groundwater drawdown. Those that can estimate groundwater drawdown ranges are shown here.

As shown in Figure 5.1, the excavation of the tunnel at the location h0 above the impermeable layer of the aquifer caused the groundwater to decline and the ground water level reaches an equilibrium state after a long period. q is the specific discharge as rainfall, and H0 is the aquifer thickness at infinity.

Bear (1972)[6] proposed an equation for the influence zone (R) of the groundwater drawdown and the steady discharge (Q) to the tunnel based on the relationship between the equation of unsteady one-dimensional infiltration to the open channel and rain infiltration. Nishigaki *et al.* (2004)[7] summarized the results of 2 - dimensional infiltration flow analysis and proposed a simple formula. These equations are summarized and shown in Table 5.3.

In the estimation based on the hydraulic formula, since the transmissivity of the aquifer and the initial water level (natural water level before tunnel excavation) greatly influence the discharge, it is necessary to carefully decide these values. The initial water level should be determined while referring to the water level in the borehole with reference to the upper surface of the layer showing the velocity of 1.5 km/sec or more in seismic prospecting. It is necessary to obtain the transmissivity by the capacity test of the aquifer. Also, it is necessary to check if it is an appropriate value compared with the discharge obtained by other methods.

6 Bear, J.: Dynamics of Fluids in Porous Media, Dover Publication Inc., pp.403-423, 1972
7 M. Nishigaki, M. Komatsu, A. Irie, K. Yano and T. Ohta: Simple prediction method and applicability of groundwater fluctuation during mountain tunnel excavation (in Japanese), J. of Japan Society of Civil Engineers, No.778/III-69、125-137, 2004.12.

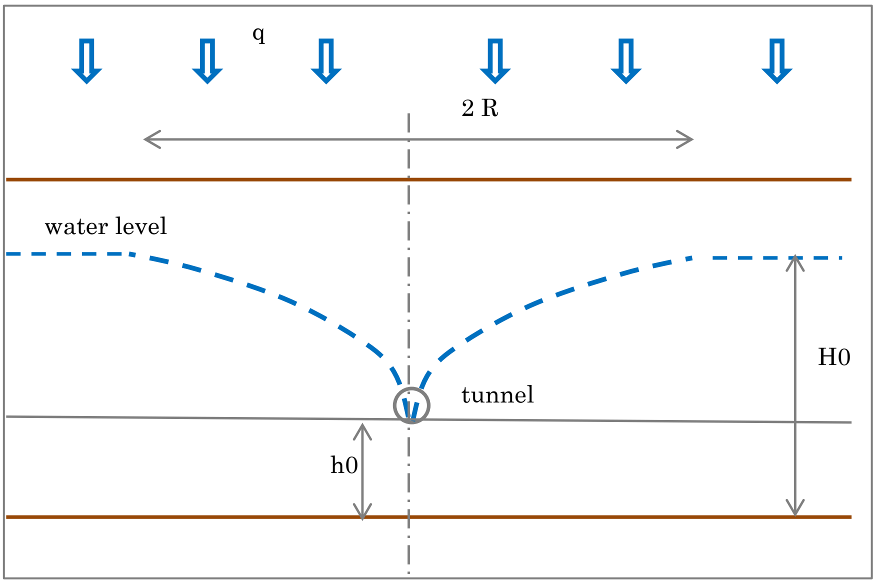


Figure 5.1 Schematic Diagram of Simplified Calculation by Using Hydraulic Formulae

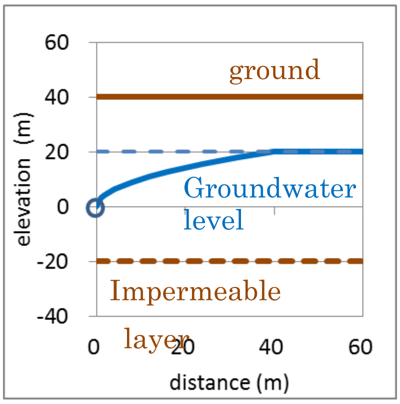
(Source: M. Nishigaki *et al.*, 2004 (in Japanese))

Table 5.3 Groundwater Drawdown Range and Discharge into Tunnel in Equilibrium Stage Based on Hydraulic Formulae
(Source: M. Nishigaki *et al.*, 2004 (in Japanese))

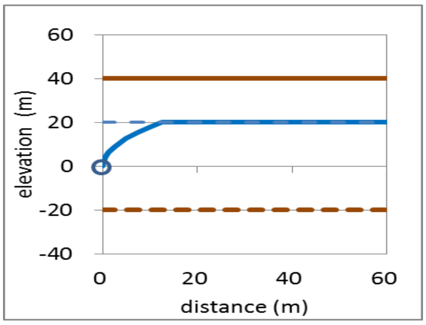
name	Groundwater drawdown range (*R*)	Discharge into tunnel in equilibrium stage (Q)
Bear	$R = \frac{1}{\sqrt{2}}\left(\frac{k}{q}\right)^{1/2} H0\left\{1-\left(\frac{h0}{H0}\right)^2\right\}^{1/2}$	$Q = \frac{k(H0^2 - h0^2)}{2R}$
Nishigaki *et al.*	$R = 1.22\left\{\left(\frac{k}{q}\right)^{1/2} - 1\right\} H0\left\{1 - \left(\frac{h0}{H0}\right)^2\right\}$	$Q = \frac{0.72k(H0^2 - h0^2)\left(\frac{k}{q}\right)^{-0.35}}{H0}$
Variables	*R:* range of draw down *k* : coefficient of permeability of aquifer *q* : rain infiltration through ground *H0* : thickness of aquifer *h0* : thickness between bottom of tunnel and bottom of aquifer	

Calculation examples by Bear's equation is shown below

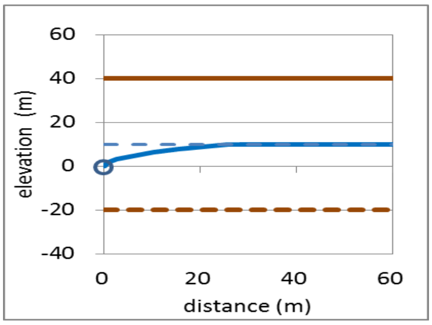
k (cm/min)	q (mm/year)	H0 (m)	h0 (m)	ground (m)		R(m)	Q(m^2/day)
0.5	1000	40	20	40		39.7	108.8



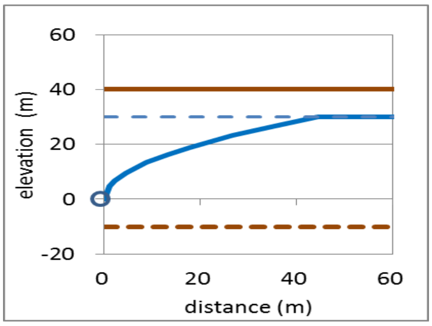
k (cm/min)		R(m)	Q(m^2/day)
0.05		12.6	34.4



H0 (m)		R(m)	Q(m^2/day)
30		25.6	70.2



h0 (m)		R(m)	Q(m^2/day)
10		44.4	121.6



q (mm/year)		R(m)	Q(m^2/day)
500		56.2	76.9

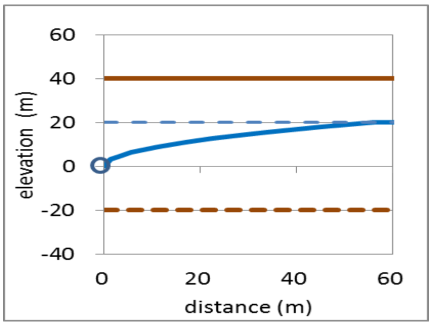


Figure 5.2 Calculation Example of Hydraulic Formula (Bear's Equation)
The values of the parameters used in the calculation and the calculation results of R (groundwater drawdown range) and Q (discharge into tunnel in equilibrium stage) are shown in the upper table of the figure. The second and subsequent columns show the changed parameter values and calculation results.
(Source: JICA project)

5.4.3 Takahashi's Forecast Method

(1) Concept of Takahashi's Method

Takahashi's method was devised for railroad tunnel excavation in Japan. Although it is a simple method, the accuracy is high, and it has been used frequently in Japan. This method was developed focusing on the similarity of the river in the dry season and the tunnel as shown in Figure 5.3. The groundwater above and around the tunnel under the equilibrium state is shown in the right figure. Takahashi (1964)[8] assumed that this equilibrium state of groundwater is the same as the water in the river in the dry season shown in the left figure. The amount of discharge into the tunnel is considered to be the same as the discharge into the river in the dry season with the same catchment area. Therefore, the equilibrium discharge into the tunnel is the product of the area of catchment and the specific discharge in the catchment area shown in the equation below.

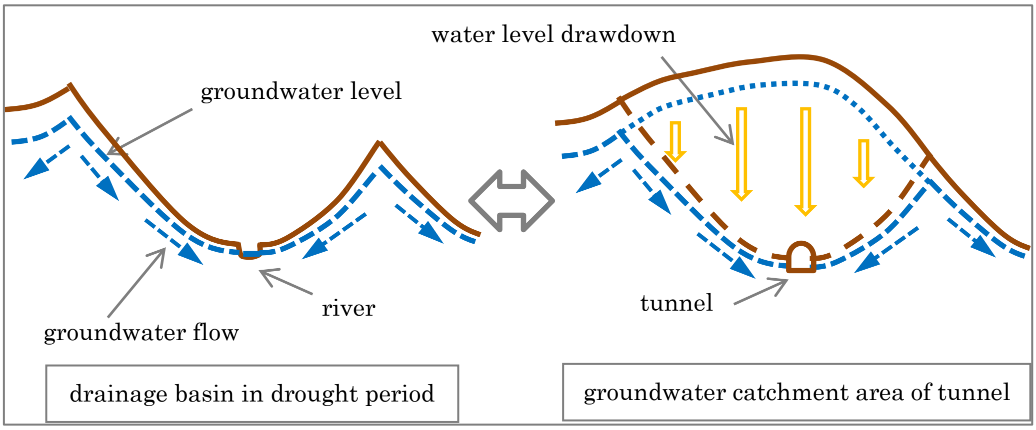


Figure 5.3 Similarity of Drainage Basin in Dry Season and Groundwater Catchment Area of Tunnel

(Source: JICA project)

$$Q = \sum qA = \sum ql(Rr + Rl)$$

Where Q: equilibrium discharge into tunnel (l/min)

q: specific discharge in unit length in dry season (l/min/km^2)

l: unit length (within same terrain and geological condition) (km)

Rr: range of groundwater catchment in the right side of tunnel (km)

Rl: range of groundwater catchment in the left side of tunnel (km)

8 Characteristics and problems of groundwater discharge into tunnel (in Japanese), J. of the Japan Society of Engineering Geology, Vol.6、No.1、25-52、1964

A: catchment area of discharge into tunnel (km^2).

Specific discharge is observed by the discharge measurement in the dry season and this is the only actual measurement data required for the calculation.

There are several methods for obtaining the catchment range, but the following three methods are mainly used: hydrological method, hydraulic method and geological method.

(2) Hydrologic Method for Catchment Area Estimation

The terrain is considered to be formed reflecting the hydrological situation. In other words, the range of the groundwater discharging to the tunnel is considered to be the same as the average width of the basin of the river near the tunnel.

The estimation procedure is as follows; A) dividing the tunnel by drainage basin and calculation of average soil covering above the tunnel, B) selection of model basin and calculation of the drainage basin width, C) calculation of the catchment area and discharge of the small tunnel segment.

A) Dividing tunnel by drainage basin into segments as shown in Figure 5.4 and calculation of average soil covering above the segments

i) The tunnel section is divided into segments (LA1, LA2, LA3 and LA4 in Figure 5.4) based on the drainage basin and the length of each segment is calculated.

ii) Soil covering thickness above each tunnel segment is estimated.

B) Selection of model basin and calculation of drainage basin width

i) Selecting model basin corresponding to each tunnel segment in the tunnel pass range or nearby so that the soil coverage of the tunnel segment and the difference in elevation between the ridgelines and the river in the model basin will be equal or nearly equal. It is preferable that the tunnel segment overlaps the model drainage basin.

ii) Calculating the drainage basin width (R) by the method shown in Figure 5.5. This drainage basin width is the range of groundwater discharge to the tunnel.

iii) Discharge measurements are carried out in the model basins during the dry season and the specific discharges are calculated.

C) Calculating of the catchment area and discharge of tunnel segment

i) Calculating the catchment area (product of the length of tunnel segment and drainage basin width corresponding to the tunnel segment) and discharge (the product of the catchment area and specific discharge) on each tunnel segment.

ii) The total amount of the discharges in all the tunnel segments is the total discharge to the tunnel.

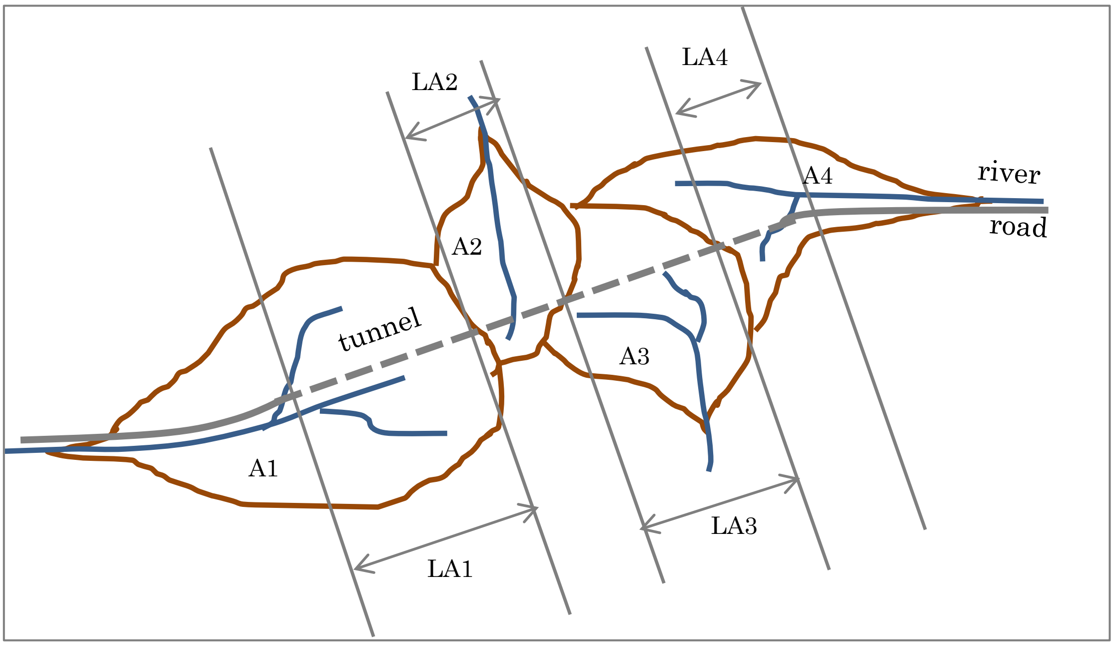


Figure 5.4 Dividing Tunnel into Segments by Drainage Basin

(Source: JICA project)

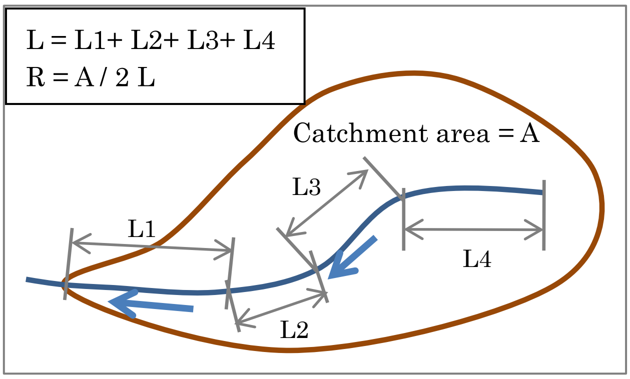


Figure 5.5 Calculation of Range of a Model Drainage Basin

(Source: JICA project)

(3) Hydraulic Method for Catchment Area Estimation

This method is also a method of estimating the catchment range, and it is used more often than the hydrological method. In this method, an average water permeability index (Kt) is used. This index indicates “the groundwater discharge range formed on one side of the open ditch in the dry season." The index is calculated by hydraulic calculation as a relational

expression between ΔH (the difference of groundwater level before and after tunnel excavation) and R (the range of influence caused by tunnel excavation) as $\mathrm{Kt} = R^2/(6\Delta H)$.
As explained in Section 5.4.3 (1), Kt can be obtained from the similarity of groundwater surface shape and land topographic shape. The method is described below with reference to Figure 5.6.
The estimation procedure is as follows; A) dividing tunnel section, selecting model basin, discharge measurement in the model basin, B) dividing the model basin into segments and calculating Kt, C) drawing a cross-section of the tunnel and topography, D) calculating R for each cross-section, E) calculating the discharge to the tunnel.

A) Dividing the tunnel, selecting a model basin, discharge measurement in the model basin

i) The tunnel passing section is divided into several sections according to topographical and geological characteristics.
ii) Model basins are selected corresponding to the characteristics near the tunnel passing area. Model basins through which the tunnel passes are desirable.
iii) Discharge measurements are carried out in the model basins during the dry season and the specific discharges are calculated.

B) Calculating Kt in the model basin

i) Connecting the highest point in the most upstream part and the exit of the river in the model basin with a straight line as shown in Figure 5.6, let the length be the flow path length L, and let the drainage basin area be A. The width of the model basin area is obtained by $\mathrm{R} = A/2L$.
ii) Dividing the model basin into several small sections with the lines perpendicular to the line connecting the highest point and the exit.
iii) The highest elevations on the right bank side on the dividing lines are Hr1, Hr2, Hrn, respectively, H11, H12. H1n on the left bank side and Hm1, Hm 2, Hmn are the elevations of the lowest points on the perpendicular lines.
iv) The average elevation difference (ΔH) of the model basin is expressed by $\Delta\mathrm{H} = \sum_k (Hrk + Hlk - 2Hmk)/(2n)$
v) Kt can be calculated from the equation of $\mathrm{Kt} = \mathrm{R}^2/(6\Delta\mathrm{H})$ in each model basin.

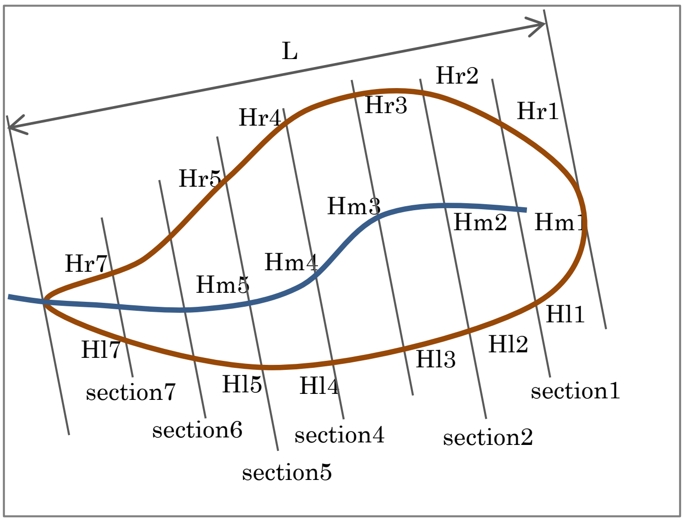


Figure 5.6 Dividing Method of a Small Model Drainage Basin

(Source: JICA project)

C) Drawing cross-section of tunnel and topography

i) Tunnel sections classified by their characteristics are further subdivided at equal intervals and the perpendicular lines to the tunnel area drawn as shown in Figure 5.7.

ii) Drawing the cross-section of the topography and the tunnel along the perpendicular line as shown in the lower figure of Figure 5.7.

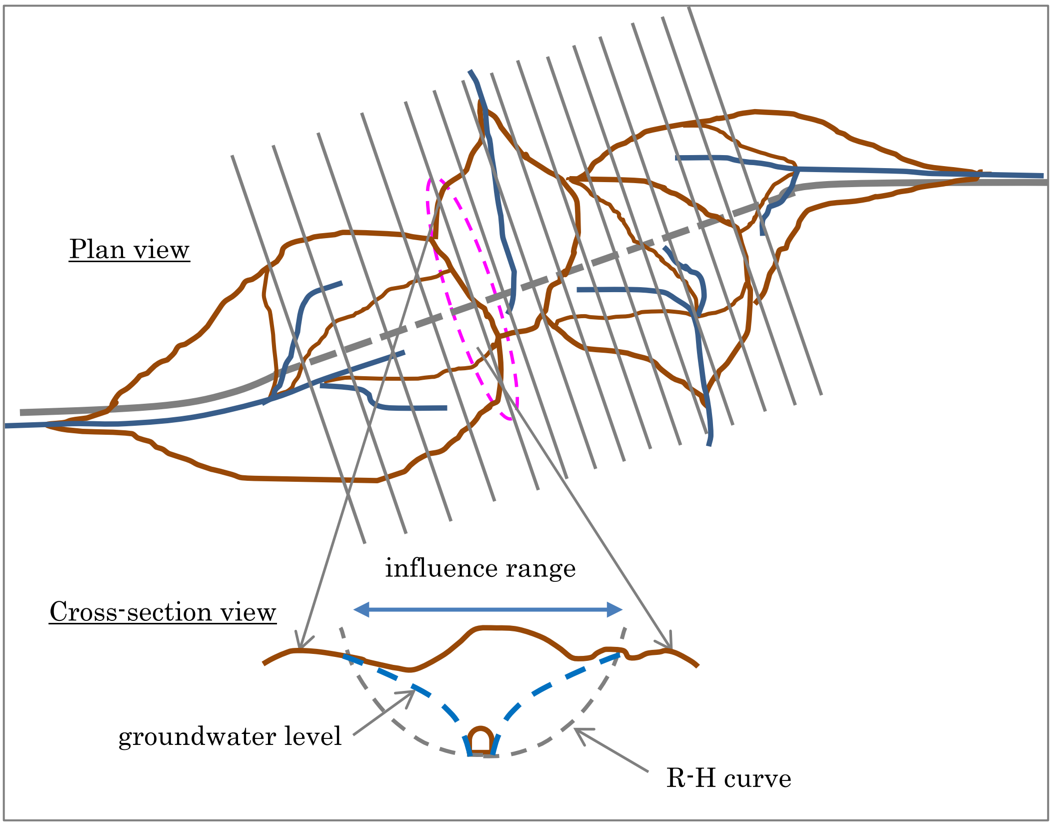


Figure 5.7 Creation of Cross-section and Calculation of Affected Area in Tunnel Basin

(Source: JICA project)

D) Calculating R for each cross-section

i) Drawing the H-R curve ($\Delta H = R^2/(6Kt)$) of the model basin corresponding to the tunnel section in the cross-sectional view with the bottom of the tunnel as the origin.

ii) The influence range of the groundwater is between the intersections with the ground surface as shown in the lower figure of Figure 5.6.

iii) Repeating the same work for each perpendicular line. The inside of the line connecting the influence range for each perpendicular line becomes the groundwater catchment area by tunnel excavation.

E) Calculating the discharge to the tunnel

i) The discharge amount into the subsection of the tunnel is calculated by multiplying the influence range, the specific discharge of corresponding model basin and the subsection length.

ii) The sum of the discharge amounts of all the subdivisions is the tunnel discharge amount.

(4) Geologic Method for Catchment Area Estimation

The geological method is a method to examine the following conditions in the catchment area obtained by the hydraulic catchment area estimation method to obtain a more accurate catchment area.

i) The groundwater catchment area is set with the ridgeline in places where remarkable valley topography exists.
ii) Distinguished watershed is considered to be the limit of the groundwater catchment area.
iii) Obvious faults are considered to be the limit of the groundwater catchment area. However, it is necessary to judge whether it is a water permeable fault in the fracture zone or the impermeable fault with clay inside.
iv) Where the fault coincides with the valley topography, the range of the groundwater catchment area is determined by the fault.
v) In the fracture zone, (permeable fault) groundwater tends to flow easily. Therefore, it is considered that the groundwater catchment area expands in the fracture zone direction.

5.4.4 Analysis by Using Tank Model

The tank model was developed by Sugawara (1972)[9] for analysis of river run-off, but it can also be applied to groundwater.

The tank model has a structure in which several water storage tanks are arranged in a series in the vertical direction as shown in Figure 5.8. Each tank is considered to correspond to the aquifer structure in the drainage basin and the groundwater infiltration is modelled by the flow down from the tank. Outlets as surface water discharge are formed on the side of the tanks and outlets indicating infiltration into the ground is provided on the bottom of the tanks. The outflow amount from these outlets is proportional to the height of water above the outlet and the diameter of the outlet. Water entering each tank sequentially flows down as surface water or groundwater and the water balance is preserved. It can be considered as an estimation method by the water balance method. The parameters of the tank model are the diameters and heights of the outlet hole. The time unit of the tank model is usually a day. The

[9] Masami Sugawara: Run-off analysis, Hydrology course (in Japanese)、 1972

Chapter 6 of "The Guide to Hydrological Practices (WMO No.168), 2009" http://www.whycos.org/hwrp/guide/index.php tank model is created by the following procedure.

i) The rainfall subtracting the evapotranspiration amount is entered in the first tank.

ii) Water levels of tanks are calculated by using water level of the previous day.

iii) Changing the parameters so that the calculation values are close to the measured river discharge.

iv) When there is groundwater data, the parameters are adjusted so that the correspondence between the groundwater level and the water depth in the tank is improved.

For forecast after tunnel excavation, changes in groundwater level and in river discharge can be predicted by adding an outlet hole corresponding to tunnel discharge.

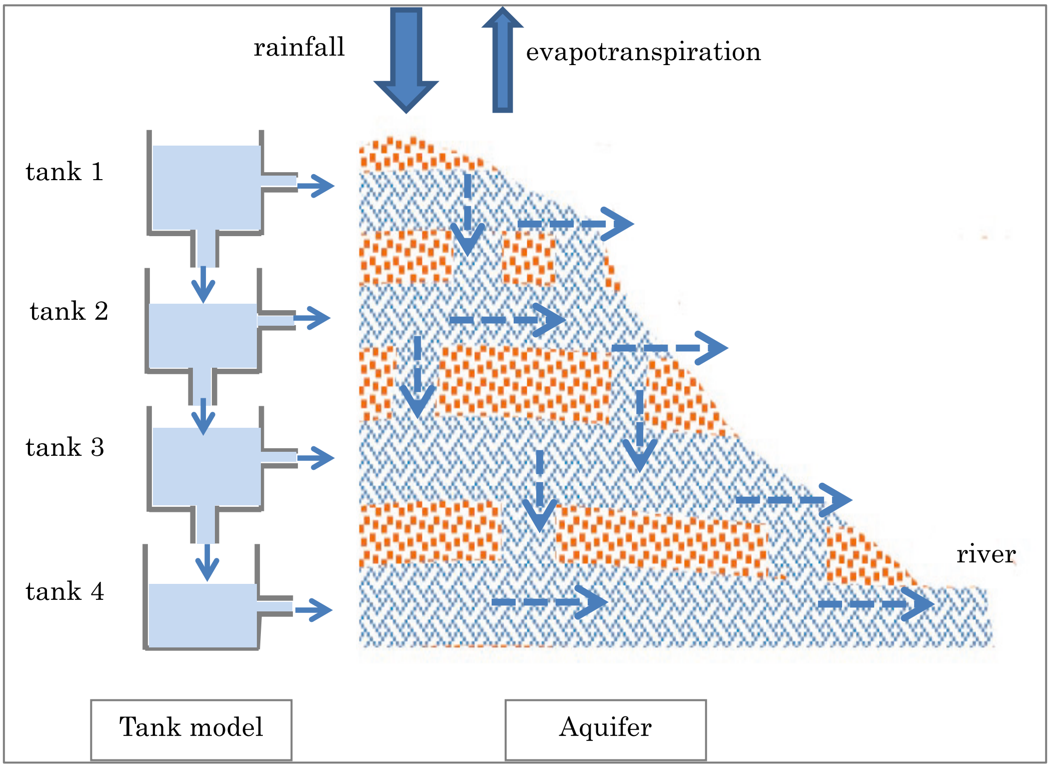
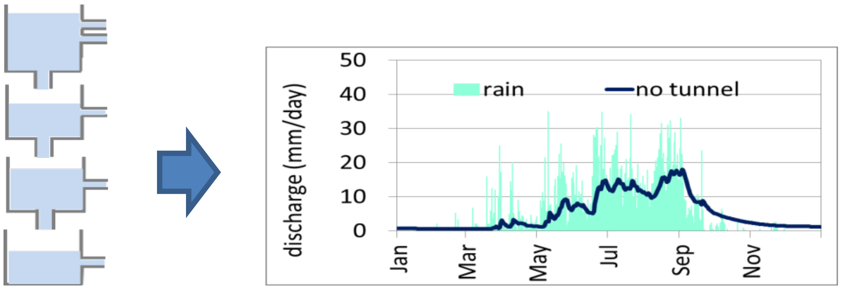


Figure 5.8 Correspondence of Aquifers and Tanks in Tank Model

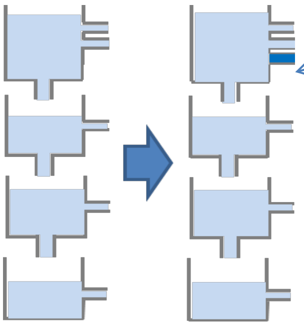
(Source: JICA project)

An example of calculation using a tank model is shown below.

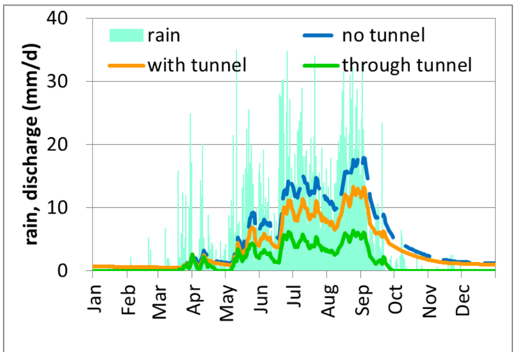
a. The parameters of Tank model are finalized after adjusting the value of the parameters so that the calculated discharge match to observed discharge.



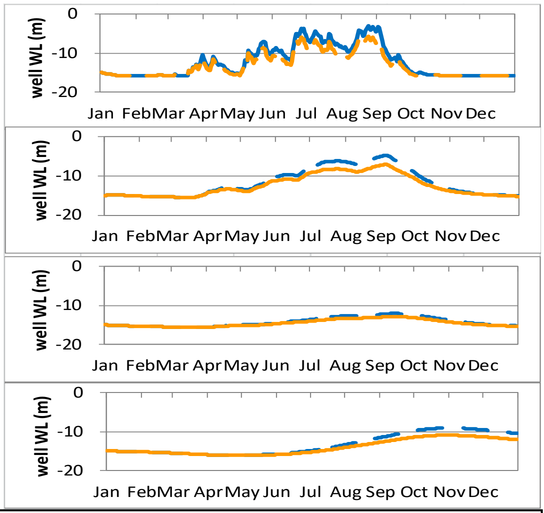
b. Adding one lateral outlet for tunnel and appropriate parameter is given then calculating discharge after tunneling work



c. Discharges and water level of the aquifer after tunneling work are obtained



This graph shows discharges before and after tunneling work.



These graphs show ground water level of aquifers corresponding to the water levels in the tanks.

Figure 5.9 An Example of Forecasting Groundwater Environment after Tunneling Work by the Use of Tank Model

(Source: JICA project)

5.4.5 Numerical Analysis by the Groundwater Simulation

Due to accumulation of knowledge and improvement of computer performance in recent years, the possibility of application of groundwater flow simulation is increasing year by year. Various models and software have been developed and are available.

Various parameters indicating characteristics of the aquifer such as transmissivity and storage coefficients are necessary to use the simulation model. In fact, investigations on groundwater and geology to build models are enormous, so additional drilling and a capacity test of the aquifer are often required. In selecting the simulation model, it is necessary to understand the characteristics of the model well, to examine the purpose of the simulation, availability of data, model accuracy, and cost. Once these are known, choose an appropriate model.

Table 5.4 Models of Groundwater Simulation

(Source: JICA project)

Model	Characteristics	Applicable target
Planar Two-Dimensional Groundwater Flow Model	・Simulating water level fluctuation of the aquifer. ・Suitable for clarifying the drawdown of groundwater level by pumping.	・Forecasting groundwater level.
Vertical Two Dimensional Groundwater Flow Model	・Dealing with groundwater flow only in one direction on the plane and in the vertical direction. ・Effective for clarifying subsidence.	・Forecasting groundwater level. ・Possible to calculate the contraction amount by strata including aquifer.
Quasi Three-Dimensional Groundwater Flow Model	・Coalescing two-dimensional plane model representing the flow of the aquifer and vertical one-dimensional model representing the flow of the pressurized layer. ・Suitable where pressure layer (clay layer) and aquifer layer (sand gravel layer) are mutual.	・Forecasting groundwater level. ・Possible to calculate consolidated settlement amount of the compression layer.
Three-Dimensional Groundwater Flow Model	・Dealing groundwater flow three-dimensionally, basically it has no constraints such as geological structure. ・Difficult to obtain necessary data because of huge amount of calculation and many variables.	・Forecasting groundwater level.

The Australian groundwater modelling guidelines (Barnett B. *et al.* 2012)[10] is a good guideline in planning to use groundwater flow simulation.

5.4.6 Model Experiments

It is difficult to quantitatively forecast the amount of tunnel discharge and the influence area only by model experiments but it may be effective if it is used in conjunction with the hydraulic formula or groundwater simulation. It is an effective tool to explain to residents and other invested parties because it is easy to see and understand.

[10] Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S,Werner AD, Knapton A and Boronkay A.: Australian groundwater modelling guidelines, June 2012、Published by the National Water Commission、http://www.groundwater.com.au/media/W1siZiIsIjIwMTIvMTAvMTcvMjFfNDFfMzZfOTYwX0F1c3RyYWxpYW5fZ3JvdW5kd2F0ZXJfbW9kZWxsaW5nX2d1aWRlbGluZXMucGRmIl1d/Australian-groundwater-modelling-guidelines.pdf

6 Investigation and Forecast during Tunnel Excavation

At the start and during tunnel excavation, the geology in the tunnel can be observed as well as measure the spring water from the tunnel. Also, since the groundwater environment is impacted as soon as tunnel excavation is started, it is desirable to continue observation of some of the EIA investigation in order to directly monitor the changing groundwater environment.

6.1 Information Obtained by Excavation

The investigation in tunnel and change of groundwater environment are conducted. The investigation factors, objects and methods of investigation are shown in Table 6.1. It is not necessary to conduct all the investigations in this table and the additional factors can be addressed as necessary.

Amount of discharge from the tunnel must be continuously monitored. The distribution of more detailed permeability and porosity can be clarified by analyzing the geological data obtained observed during excavation and measuring the amount of discharge.

Measurements made prior to excavation for EIA such as meteorological parameters, discharge of surface water / spring water, water level of wells for observation and water use, water quality, etc. should be continued during excavation. Those changes are always monitored, and the data are continuously updated. Continuous observation of groundwater level is indispensable because it can directly indicate the effect of excavation.

Table 6.1 Factors, Objects and Methods of Investigation during Tunneling Work
(Source: JICA project)

Factors	Objects	Methods
Land use, land cover	Land use, land cover, vegetation, Animals and plants	Site survey
Soil,	Soil distribution, soil moisture, existing structure	Site survey, measurement
Geology	Geological structure in tunnel	Site survey
Meteorology	Rainfall, evapotranspiration	Data collection, meteorological observation
Surface water	Discharge of river, water usage, water quality	Data collection, hydrological observation, water quality analysis
Sspring	Discharge of spring, water usage, water quality	Data collection, hydrological observation, water quality analysis
Well	Water level, water usage, water quality	Data collection, observation
Hydrogeology	Structure and properties of aquifer	Measurement discharge from tunnel

6.2 Improvement of Forecast

The forecast is improved by using data obtained during excavation and from continuous observation. If necessary, environmental conservation measures should be reviewed as well.

7 Environmental Protection Measure, Evaluation and Follow-up Investigation

7.1 Environmental Protection Measures

7.1.1 Concept of Environmental Protection Measures

The purpose of environmental protection measures is to avoid or reduce the effect of implementation of target projects to the extent practicable by the project implementer. Environmental protection measures are broad measures which include measures to avoid environmental impacts and measures to compensate for unavoidable effects. These measures are described for each classification of measures and are shown in Table 7.1. Since environmental protection measures are reflected in the project plan, it is important and necessary to consider and organize these measures, as specifically as possible, in accordance with the progress of the project plan.

Table 7.1 Avoidance, Reduction and Compensation in EIA

(Source: JICA project)

Classification	Contents
Avoidance	Measures to avoid the impact by not executing all or part of the projects that may impact the environment. It is also avoidance of factors expected to have serious effects and are kept away from. Example: change of project area, change of route
Reduction (Minimizing, Rectifying, Reduction, Elimination)	Measure to reduce or minimize the influence by limiting the extent or scale of the project implementations as an influential factor and / or by some means to reduce or disperse the influence. Example: reduction of project scale, change of shape, change of construction method to minimize groundwater flow disruption, or installation of water treatment facility.
Compensation	Compensation for the value from the viewpoint of environmental protection by creating the same kind of environmental factors as the factors damaged by project implementation.

7.1.2 Procedure for Planning Environmental Protection Measure

Procedures for planning environmental protection policy are as follows:

i) Policy setting of protection

Objects and goals of environmental protection measures are set. It is important to select the objects of environmental protection by paying attention to the entire hydrologic system of the target area. It is also necessary to pay attention to the water use situation and ecosystem of the target area.

ii) Consideration of the contents of avoidance and reduction

Specific details of avoidance / reduction measures are considered. The consideration is also given to measures to compensate for the remaining effects that cannot be avoided or reduced.

iii) Consideration of the effects of avoidance / reduction

Effects of avoidance / reduction are considered objectively. In the case where uncertainty remains, its extent is also clarified.

iv) Consideration of the influence on other environmental factors

The influence on other environmental factors due to implementation of avoidance / reduction measures and the remaining effects despite taking avoidance / reduction measures are considered.

v) Selection of the optimal plan for implementation of environmental protection measures

The process of ii) > iii) > iv) > ii) is repeated to verify the adequacy of environmental protection measures. After satisfactorily completing the iterative process, the optimal plan for implementing environmental protection measures is selected.

7.1.3 Contents of Environmental Protection Measure

It is important to consider the measures from the viewpoints of technology, cost, reality and concreteness because environmental protection measures must be feasible.

7.1.4 Validation Analysis of Environmental Conservation Measures

Consideration of environmental protection measures is basically done by comparing multiple proposals and using better executable technology. The effect, uncertainty, influence on other environmental factors, etc. of each multiple protection measures are considered, and the measures judged to be able to obtain the effect properly is adopted. It is necessary to concretely show the effect of environmental protection measures by reference to the latest research results and similar cases, guidance by experts, and implementation of preliminary tests as necessary. In the case where uncertainty remains, its extent is also clarified.

7.2 Evaluation

7.2.1 Evaluation on Avoidance and Reduction

Evaluation concerning avoidance / reduction is a judgment based on objective examination of the effect of environmental protection measures adopted and the validity of the technology objectively. As a method for achieving this, a time series or parallel comparison study of multiple proposals and the use of better executable technology are considered.

The impact of the project may affect various environmental factors in the EIA for groundwater. It is also conceivable to evaluate from the viewpoint of not changing the state of each constituent element in the present situation as much as possible, such as minimizing changes in groundwater level and groundwater quality.

7.2.2 Evaluation on Validity to Standards or Target

In the case where there are environmental criteria / targets indicated by environmental standards, local environmental organizations on environmental protection, environmental basic plan, environmental conservation ordinances, environmental conservation plans / guidelines, the consistency with those criteria / targets is examined.

In carrying out environmental preservation measures such as water circulation of groundwater, etc., there are cases which take time until the effect or influence comes out.

7.3 Follow-up Investigation

7.3.1 Concept of Follow-up Investigation

In implementing environmental protection measures related to the hydrologic cycle such as groundwater, there are also cases in which it takes time until the effect or influence comes out. Also, uncertain factors are expected in its effect and impact. Therefore, it is important to conduct a follow-up investigation and to try to clarify the effect and impact of the project. The following process is important:

i) To judge whether the predicted impact is within the forecast range,

ii) To clarify whether environmental protection measures are fully functioning and showing effects,

iii) To add and review environmental protection measures as necessary, in the case that a remarkable environmental impact exceeding the forecasting result is confirmed.

7.3.2 Contents of Follow-up Investigation

(1) Factors, Objects and Method of Follow-up Investigation

The method of the follow-up investigation is basically the same as the method of the EIA because the purpose of the follow-up investigation is the comparison of the forecast of the EIA and the follow-up investigation. It is also necessary to clarify the purpose of the follow-up investigation and to devise methods to meet the purpose.

The investigation factors, objects and methods of follow-up investigation are shown in Table 7.2. It is not necessary to conduct all the investigations in this table and other necessary factors can be added as necessary.

Table 7.2 Factors, Objects and Method of Follow-up Investigation
(Source: JICA project)

Factors	Objects	Method
Land use, land cover	Land use, land cover, vegetation, Animals and plants	Site survey
Soil,	Soil distribution, soil moisture, existing structure	Site survey, measurement
Meteorology	Rainfall, evapotranspiration	Data collection, meteorological observation
Surface water	Discharge of river, water usage, water quality	Data collection, hydrological observation, water quality analysis
Spring	Discharge of spring, water usage, water quality	Data collection, hydrological observation, water quality analysis
Well	Water level, water usage, water quality	Data collection, observation
Hydrogeology	Structure and properties of aquifer	Measurement discharge from tunnel

(2) Sites of Follow-up Investigation

The sites of the follow-up investigation are selected based on the sites expected to be most affected by the project implementation and the sites where the forecast was made. The sites for understanding the background is set at the sites where influence of the project is hardly expected based on the forecast in the EIA

(3) Implementation Time of the Follow-up Investigation Implementation

The implementation time of follow-up investigation is set based on continuous monitoring and forecasting. Because the impact of some factors will become apparent after a long time, it is also necessary to consider these factors and the time reviewed.

(4) Utilization of Follow-up Investigation

Continuous monitoring needs to be positively utilized for clarifying the extent of the impact on the environment and the extent of the effect of EIA. Likewise, it is desirable to utilize effectively the results of investigations – observation data of flow / water quality, groundwater level and ground subsidence, and complaint investigations, etc. - conducted by non-business operators, such as public agencies and local governments.

7.3.3 Additional Consideration of Environmental Protection Measures

It is fundamental to appropriately implement additional environmental protection measures, in case the follow-up investigation identifies significant environmental impact.

7.3.4 Public Announcement

If it is judged that additional measures are necessary based on the results of the follow-up investigation, it is necessary to disclose the results and opinions on how to cope with such additional measures.

Even if the need for additional measures is not recognized and the effect of measures is recognized as predicted from the results of the follow-up investigation, the results of the follow-up investigation will be announced including the contents.

The results of the follow-up investigation should be released as soon as possible after the investigation. It is especially important to make follow-up results public as soon as possible during the project implementation because the situation of the environment may change during the progress of the project.

7.3.5 Utilization of the Results of Follow-up Investigation

It is important that the results of the follow-up investigation are aggressively organized, analyzed and utilized for the following reasons:

- To establish an appropriate investigation method,
- To improve forecast accuracy,
- To provide objective information on examining the effect of environmental protection measures, and
- To provide valuable information that contributes to improving future EIA technology

For that purpose, it is desirable to make the results of the follow-up including basic data, accessible to interested parties. It is also advisable to create a mechanism to make use of it.