Journal of Geosciences, Osaka City University
Vol. 46, Art. 11, p. 169-191, March, 2003

Selection of Appropriate Concept of Extractable Groundwater Yield

HATA Yuichi

Consulting Division, Environment & Water Resources Department, Pacific Consultants International.
1-7-5 Sekido, Tamashi, Tokyo 206-8550, Japan. E-mail: hatay@pcitokyo.co.jp

Abstract

Although concepts of extractable groundwater yield seem to differ in name only, they in fact are based on different scale of water sources. Without such differentiation, the concepts are often improperly used in practical field of development in developing countries. These concepts can be grouped into 5 categories: A) critical pumpage capacity for individual well, B) appropriate utilizable quantity for multiple wells, C) withdrawable amount for groundwater use from a basin, D) extractable yield on non-renewable groundwater basin and E) permissible level in groundwater development and conservation. In order to examine the adaptability of the concepts to the practical project, case studies have been made. As a result, it is ascertained that the concept of "critical pumpage capacity for individual wells" is valid only for the project in basement terrain with no environmental impact risks. In other projects, however, the concept of "permissible yield" must be applied.

Key-words : Groundwater, Extractable Yield, Groundwater Development, Groundwater Basin Management, Permissible Yield

Introduction

In most developing countries, groundwater development projects have been extensively implemented to cope with the rapid growth of water demand. On these groundwater development projects, the highest priority is always given to humanitarian ideals of the moment such as urgent need for drinking water supply and basic human needs. Consequently, the projects give priority to "development" without much consideration to "management" of groundwater resources. Hence, problems related to environment and water source sustainability commonly occur.

An important factor for groundwater use and management is not the "technique of exploitation and development", but the "estimation method for extractable yield of groundwater". In past projects for groundwater development, various concepts of groundwater yield have been proposed and utilized. The application of such concepts for practical projects both in and outside Japan, however, have been confused.

Although, these concepts differ in their applicable scope, there is no precise guideline to appropriate usage. Moreover, in practical field development, the concept has been misused. As a result, realization of projects has progressed only by calculating the amount for development from the amounts of hydraulic maximum pumping rate from a single well.

The establishment of the estimation method for extractable yield of groundwater, in order to evaluate the possibility of groundwater development and use, is an international theme of great importance. The main purpose of this study, therefore, is to select the appropriate concepts of extractable groundwater yield, by examining the adaptability of the groundwater yield concepts for practical projects.

There are two words related to groundwater amount: namely, "storage capacity" and "yield". The "storage capacity", is the amount of groundwater stored in the aquifer or groundwater basin. On the other hand, the "yield" (which is also called "pumping rate") is the extractable groundwater amount from the aquifer or groundwater basin by the artificial activities (Shibasaki, 1976). In this study, the author deals with these concepts for groundwater yield. In recent years, groundwater pollution is being highlighted as a social issue resulting from society's productive activities, other than the environmental problems caused by groundwater pumpage. In the newly industrialized countries, there are latent risks of groundwater pollution caused by geological disposal and underground infiltration resulting from disposal of industrial wastes. In such pollution, it is required to use countermeasures in a manner different to the problems of groundwater yield. Meanwhile, groundwater pollution caused by natural contamination such as salt water, arsenic and fluorine are being frequently reported in the world. In the Bengal lowland area of Bangladesh (Shibasaki, 1997) and Inner Mongolia of China (Gao, 1997), for example, the regional arsenic contamination of groundwater has caused severe suffering. The mechanism of such contamination of groundwater has not been elucidated yet, since it is due to complex factors. On the other hand, it is pointed out that the contamination is expanding by the rapid decline of groundwater level resulting from the groundwater pumpage (AAN et al., 1999). Accordingly, the discussion on groundwater yield control is significant. In this study, therefore, the author focuses on the quantitative issues of the groundwater management and use.

Concepts and categories of groundwater yield

A total of nine terms for the concept of groundwater yield have been identified (Hata, 1998). They are two types of optimal yields (1) (Murashita, 1962); (2) (JWWA, 1990), appropriate utilizable yield (MITI, 1965), optimal critical discharge (Kurata, 1960), safe yield (Lee, 1915), perennial yield (Todd, 1976), sustained yield (ASCE, 1961), mining yield (ASCE, 1961) and permissible yield (Shibasaki and Kumai, 1968). Hata (1998) classified these nine terms into the following five categories (Table 1).

Category A is characterized as the critical pumpage capacity of a single well which is estimated by a pumping test. The area of the application is appropriate for an individual well. The terms of optimal yield (1) and optimal yield (2) are associated with this category. The optimal yield (1) is identified as the pumping rate obtained by an overlapping point of upward and downward curves in a graph of a step drawdown test, while the optimal yield (2) is the pumping rate of a certain percentage of the critical discharge rate. Category B is applied for a well field (multiple wells). This category includes two terms of appropriate utilizable yield and optimal critical discharge. In either case, however, hydraulic rate is estimated by aquifer constants and consideration of head loss due to mutual interference of the wells. Category C includes three terms: safe yield, perennial yield and sustained yield. The concept of this category is based on withdrawable amount of groundwater use from a basin-wide viewpoint, with due consideration to equilibrium of water balance of the basin. Category D includes only one term: mining yield. The

Table 1 Identified terms of the groundwater yield concept and its categories. After Hata (1998), modified by Hata.

No.	Concept	Description	Category	Scale of Water Source
1	Optimal yield (1)	Critical pumpage capacity for individual well	A	Individual well
2	Optimal yield (2)			
3	Appropriate utilizable yield	Quantitative control for well field	B	Multiple wells
4	Optimal critical discharge	Area of influence for multiple production well		
5	Safe yield	Withdrawable amount for groundwater use from a basin wide	C	Groundwater basin
6	Perennial yield			
7	Sustained yield			
8	Mining yield	Extractable yield on nonrenewable groundwater basin	D	
9	Permissible yield	Permissible level in groundwater development and preservation	E	

applicable scope of the term is also appropriate for a groundwater basin. Harmonious water balance, however, is not applicable for this category. The category is characterized by the extractable amount of non-renewable water from a groundwater basin. Category E incorporates only permissible yield from among the nine terms. The methodology of the term is basically equivalent to Category C. The concept of the category, however, is limited not only by "harmonious water balance", but also by relevant socioeconomic aspects.

In the practical projects in developing countries, utilization of the yield concepts is concentrated on either Category A or B (Hata, 1999). The utilization of other categories is very rare. A similar situation is identified in the guidelines and regulations related to groundwater development in Japan, for example:" A series of laws on regulation for groundwater extraction (JGTA, 1962)", "A guideline for design of water supply facilities (JWWA, 1990)", "Estimation standard for water well drilling (NWWA, 1993)" and "Guideline for investigation and observation for groundwater (JICE, 1993)". All of them were based on the concepts of Category A or B for the determination of groundwater (well) yield.

The method of determination of groundwater yield should primarily be selected based on the scale of water source (Hata, 2000). The scales consist of three yields: namely, "Well Yield", "Aquifer Yield" and "Basin Yield". The concepts of optimal yield (1) and (2) of Category A are suitable for the scale of "Well Yield", because these yields are determined by the hydrological estimation of a well. The concepts of appropriate utilizable yield and optimal critical discharge of Category B are suitable for the scale of "Aquifer Yield", since these yields are determined based on quantitative control and/or area of influence of multiple wells in the same aquifer. The method for determination of yield is also based on the hydraulic estimation of multiple wells. The concepts of safe yield, perennial yield, sustained yield, mining yield and permissible yield of Categories C, D and E are suitable for the scale of "Basin Yield" since these yields require consideration of groundwater basin management.

Items to be examined for proper groundwater development and use

The consideration of the groundwater basin as a total system is an essential factor in managing groundwater development and use. The concepts of groundwater yield, which are associated with this hydrogeological unit, are: safe yield, perennial yield, sustained yield, mining yield and permissible yield. These concepts are expressed in the term "Basin Yield". Among these concepts, however, the only term, which has a socioeconomic parameter, is the permissible yield. The techniques of water balance simulation in a groundwater basin are generally required to determine the basin yield. In addition, an environmental consideration is required to determine the permissible yield. In this section, the role of four major factors in determining the permissible yield and/or basin yield for the groundwater development project will be examined. These factors are: 1) possible environmental impact, 2) system to be clarified and required data, 3) study period and 4) management level (Hata, 2001).

Possible environmental impact

There are two types of environmental problems related to groundwater development and use (Shibasaki and Research Group for Water Balance, 1995). One of these is caused directly by the decline of groundwater level including cessation of artesian conditions of springs and/or wells, head loss due to the mutual interference of the well and reduction of yield in neighboring wells. The other type deals with problems caused by the induced phenomenon due to significant decline of groundwater level, which includes land subsidence, groundwater pollution and seawater intrusion. Usually, these risks differ in degree according to the geological region. Table 2 shows the general degree of risks for three different geological regions: consolidated basement terrain, pyroclastics terrain and sedimentary basin, and an example from the East Java province of Indonesia (Hata, 2001)

As shown in Table 2, there are medium or high risks of problems directly caused by the decline of groundwater level in any geological region. On the other hand, most of the problems caused by the induced phenomenon due to significant decline of groundwater level are low in consolidated basement terrains and pyroclastic terrains (except for seawater intrusion), although sedimentary basins have high risks. A conditional risk for seawater intrusion is suspected in coastal areas underlain by limestone or permeable volcanic sediments, for example.

System to be clarified and required data for groundwater simulation

One of the objectives in groundwater basin management is to determine the environmental carrying capacity of groundwater in specific regions, and then to

Table 2 Relationship between geological regions and risks of environmental problems. After Hata (2001), modified by Hata.

Problems / Geological regions	Problems directly caused by the decline of groundwater level			Problems caused by the induced phenomenon due to significant decline of groundwater level		
	Cessation of artesian conditions	Head loss due to mutual interference	Reduction of yield of neighboring well	Land subsidence	Groundwater Pollutions	Seawater intrusion
Consolidated basement terrains	**Medium**	**Medium**	**Medium**	**Low**	**Low**	**Medium**
Pyroclastics terrains	**Medium**	**Medium**	**Medium**	**Low**	**Medium**	**Medium**
Sedimentary basins	**High**	**High**	**High**	**High**	**High**	**High**

Remarks :

Low	The risks for environmental problems are **low**.
Medium	Certain measure of risks, or the conditional risks are **latent**.
High	The risks for environmental problems are **high**.

set up specific action plans to effectively utilize the resources. Therefore, prediction of change in groundwater behavior is required before the design stage. Based on this background and those requirements, the technique of groundwater simulation has been developed. To prepare an appropriate model and to perform a precise prediction, the water balance comprising the systems of recharge, basin and discharge must be clarified (Fig. 1).

Periodical record of observation for at least 10 or more hydrological years is generally required for the meteorological and hydrological data necessary for the recharge and discharge systems. To understand the hydrogeological mechanism of the groundwater basin, configuration and characteristics of the aquifer must be clarified. Therefore, a detailed geological investigation is normally required.

Study period allocated

The study period restricts the use of groundwater yield concepts. This is because each yield concept has a different method for its determination. As shown in Table 3, the terms of yield concepts, which generally cover the groundwater basin need a study period of more than 24 months. These concepts are: safe yield, perennial yield, sustained yield, mining yield, and permissible yield. The required study period for the determination of basin yield is based on the availability of the data. The period required for the groundwater simulation differs in terms of purpose and required accuracy. In a practical sense, a longer study period is desirable for groundwater simulation to manage the groundwater use. However, if all data necessary for the execution of the groundwater simulation are available, in general, basin yield can be determined by the middle of the study period (12 to 24 months). On the other hand, for the other yield concepts of optimal yield (1) and (2), appropriate utilizable yield and optimal critical discharge can be determined even in a short study period

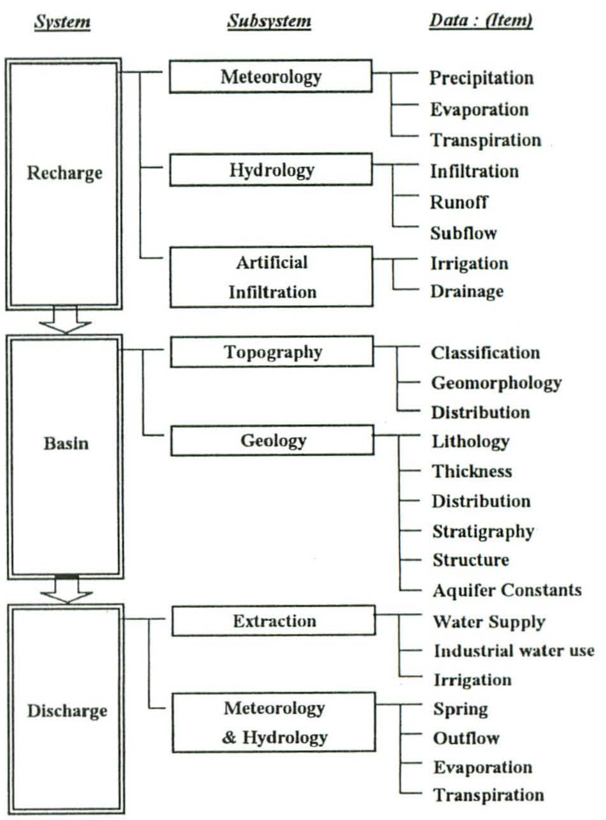


Fig. 1 The systems and necessary data to be examined for the clarification of water balance of the basin. After Hata (2001), modified by Hata.

of less than 12 months. Since these yield concepts are determined only by hydraulic parameters, a long study period is not necessary.

Management level

The steering committee of groundwater modeling assessment project of the American Geophysical Union (AGU, 1978) pointed out that usability of groundwater models varies by size of management level. Figure 2 shows usability of the groundwater basin management by its management level. Use of groundwater model, in this case, designates the use of the concept of "Basin Yield".

For small-scale management levels such as those of small districts (villages) and private developments (factories or firms), it is not economical to use groundwater models. The yield concepts related to well yield or aquifer yield are much more convenient to use for such small-scale management levels. A risk frequently latent in this situation, however, arises if many private wells accumulate in the same groundwater basin. Large-scale management levels such as state and province are too large for the groundwater basin management. Recently, however, the size of the area for which groundwater simulation can be applied is increasing as the computer technology advances. However, in terms of implementation and the operation stages of the project, since the water supply areas are often scattered all over the groundwater basin, the use of groundwater models at such level is still not economical, especially in developing countries. The middle-scale management levels such as metropolitan and municipal are ideal levels for groundwater basin management. For these levels, it is easy to manage the development and use of the groundwater by coordinating all districts impacting on the same basin. Hence, it is concluded that basin management is not appropriate for every management level. Management levels of metropolitan and municipal are the levels, which suit basin management.

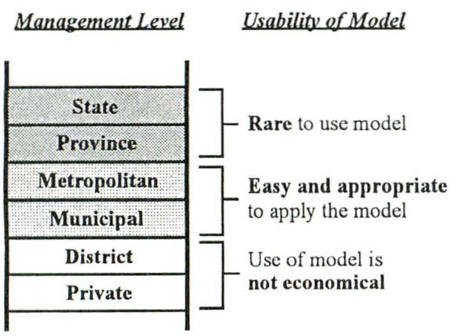


Fig. 2 Management level and usability of groundwater model. After American Geophysical Union (1980).

Case studies

In order to study the role evaluation factor, three case studies are presented below.

Case study-1, Community water supply project

Project digest

The project selected for the case study of community water supply project is "Groundwater Development Project (Phase-II) in Southern Province" in the Republic of Zambia (JICA, 1988). Since 1981, the

Table 3 Adaptability of each yield concept by study period. After Hata (2001), modified by Hata.

No.	Concepts of yield	Study Period		
		Short period (less than 12 months)	Middle period (12 - 24 months)	Long period (more than 24 months)
1	Optimal yield (1)	**Possible**	**Possible**	**Possible**
2	Optimal yield (2)	**Possible**	**Possible**	**Possible**
3	Appropriate utilizable yield	**Possible**	**Possible**	**Possible**
4	Optimum critical discharge	**Possible**	**Possible**	**Possible**
5	Safe yield	**Impossible**	**Partial**	**Possible**
6	Perennial yield	**Impossible**	**Partial**	**Possible**
7	Sustained yield	**Impossible**	**Partial**	**Possible**
8	Mining yield	**Impossible**	**Partial**	**Possible**
9	Permissible yield	**Impossible**	**Partial**	**Possible**

Possible : **Possible** to analyze within the period
Partial : **Partial** analysis possible within the period
Impossible : **Impossible** to analyze within the period

province experienced frequent droughts during which most of dug wells and streams dried up. The project was planned for emergency relief purposes from the drought by providing safe and stable water from tube wells to the rural inhabitants. The plan includes construction of 220 hand pump wells for the selected communities in the Southern Province. The locations of proposed hand pump wells are shown in the geological map (See, Fig. 3).

Hydrogeological study

Electric explorations using the Schlumberger electrode configuration method were carried out to examine the hydrogeological structure of the area. The explorations were carried out at two different formations of Basement Complex (Precambrian metamorphic rocks) and Karroo System (Mesozoic sedimentary rock). The profile of Gwembe site shows the hydrogeological structure of the Basement Complex (See, Fig. 4). Since the northern part of the profile has high resistivity of more than 2,000 ohm-m, it suggests that the basement rock is hard and compact, even at surface. On the other hand, the majority of the profile shows a 4 layered model as follows: 1st layer with a resistivity range of 550 to 880 ohm-m which suggests that it is the overburden of the area, 2nd layer with a resistivity range of 190 to 320 ohm-m, 3rd layer with a resistivity range of 35 to 155 ohm-m which suggests that it contains the expected aquifer by the weathered rocks, and 4th layer with high resistivity of more than 1,500 ohm-m which suggests that it is fresh basement rock.

The profile of Sivonga site shows the hydrogeological structure of the Karroo System (See, Fig. 5). A major anomaly was detected at the center of the profile, showing high resistivity of more than 1,800 ohm-m. The resistivity structure suggests that a geological boundary or a fault runs through this anomaly. The majority of the profile, meanwhile, shows the 4 layered model composed of: 1st layer with a resistivity range of 330 to 640 ohm-m which suggests it is the overburden of the area, 2nd layer with a resistivity range of 120 to 290 ohm-m, 3rd layer with a resistivity range of 15 to 40 ohm-m which suggests that it contains the expected

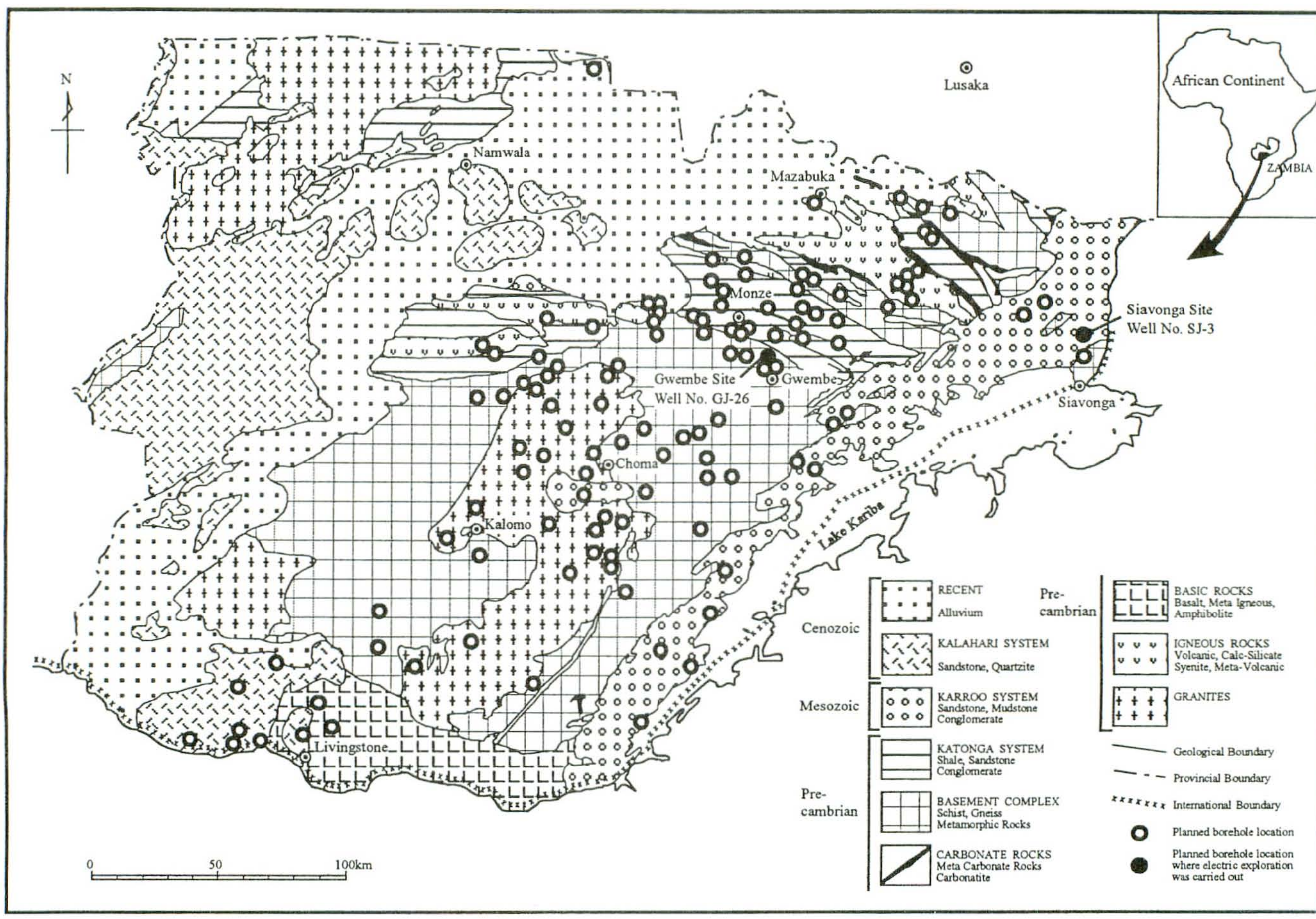


Fig. 3 The location of hand pump wells shown on the geological map of the southern province of Republic of Zambia. After JICA (1988), modified by Hata.

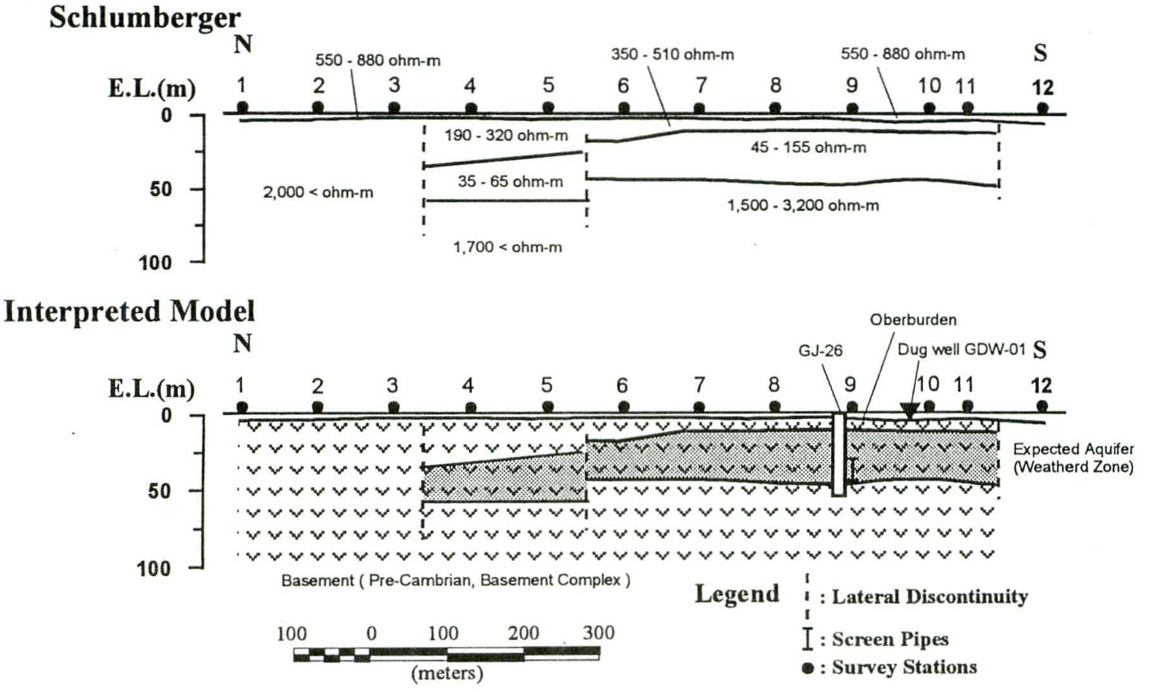


Fig. 4 Resistivity profiles of Gwembe site.

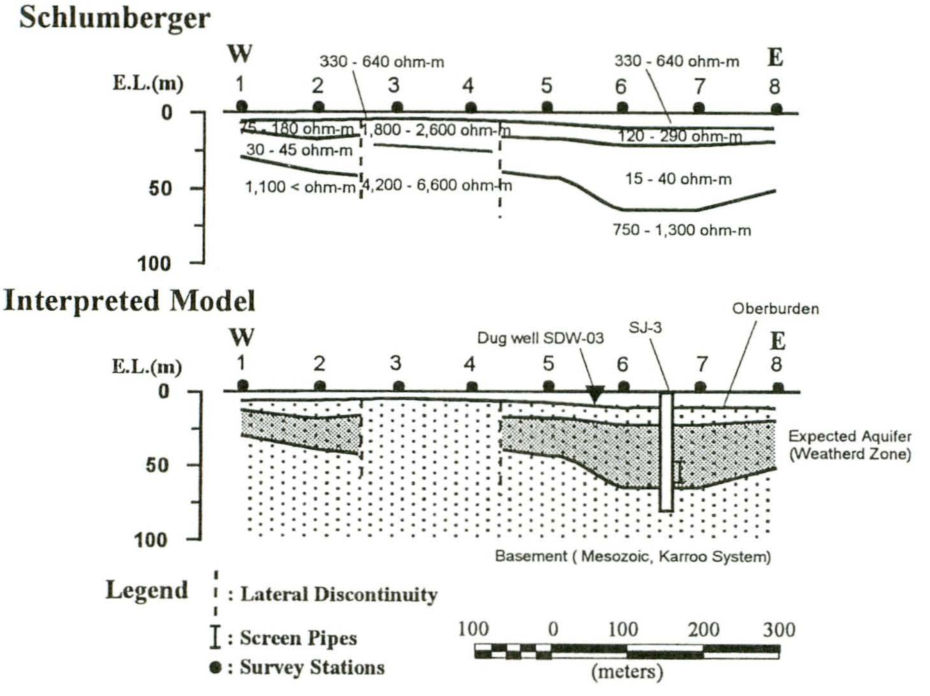


Fig. 5 Resistivity profiles of Sivonga site.

aquifer in sedimentary rocks and 4th layer with high resistivity of generally more than 1,000 ohm-m which suggests that it is the basement.

In the province, groundwater has been generally exploited by dug wells for domestic use. These dug wells have their depths ranging from 5 to 10 m. The surface overburden, therefore, is detected as a shallow aquifer utilized by the existing dug wells. In the project, tube wells were drilled mainly to the deeper aquifer in the weathered zone of the basement rocks.

Pumping test

Fig. 6 shows the results of the constant discharge test and recovery test of the wells GJ-26 and SJ-3, which correspond to the resistivity profiles of Gwembe and Sivonga sites, respectively. The aquifer properties of each well are summarized in Table 4. During the measurement of water level in the pumped well, the measurement of water level for an existing dug well was performed. Such dug wells are GDW-01 for pumped well GJ-26, and SDW-03 for pumped well SJ-3. Well GJ-26 was drilled at station No. 9 of the profile Gwembe site with its depth 60 m; screen pipes are installed from 35 to 47 m (See, Fig. 4). Well SJ-3 was drilled between Stations Nos. 6 and 7 of the profile Sivonga site with its depth 75 m; screen pipes are installed from 34 to 52 m (See, Fig. 5). The results of the pumping test showed different static water levels. Small fluctuations of water level in both existing dug wells were recorded. The range of the fluctuation is 0.5 to 1.4 cm. However, since these fluctuations do not correspond with the drawdown curves of pumped well, it is judged that the roots of the fluctuations are not head loss by the pumped wells, but measurement error or pumping of neighboring dug well by inhabitants.

Examination of an applicable yield concept

Based on the results of hydrogeological study and the pumping test, an applicable yield concept of the project was examined. An evaluation sheet to examine an applicable yield concept of the project is shown in Table 5. The results of the case study are summarized below.

i) The aquifer constants reveal that the potential level of the well is poor. However, the pumping rate of hand pump to be installed in the wells for the project is at most 15 liter/min. The water levels of dug wells were almost stable even after 72 hours of continuous pumping of the tube well. Pumping water therefore, will not affect the groundwater level of the existing dug wells. Considering the geological conditions of Pre-Mesozoic consolidated basement rocks of the project area and the

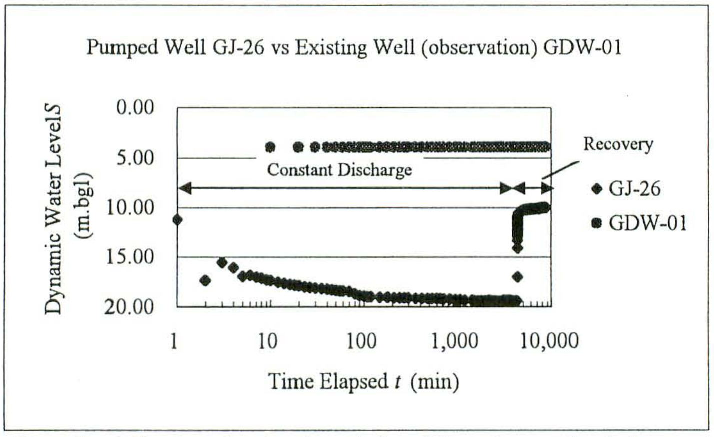


Chart 6a The chart showing the variation of dynamic water level of pumped Well (GJ-26) and existing well (observation) GDW-01

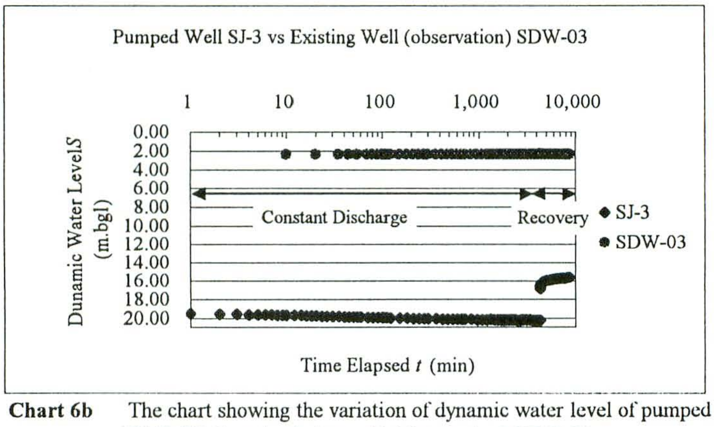


Chart 6b The chart showing the variation of dynamic water level of pumped Well (SJ-3) and existing well (observation) SDW-03

Fig. 6 Interaction between the pumped wells and dug wells, southern province of the Republic of Zambia.

Table 4 Aquifer properties of test wells GJ-26 and SJ-3 in the Southern Province, Republic of Zambia.

Well No.	Pumping Rate (l/min.)	Drawdown (m)	Specific Capacity (l/min./m)	Transmissivity $T(m^3/day/m)$	Permeability K (cm/sec.)	Storativity S
GJ-26	26	9.4	2.77	4.73	4.56×10^{-4}	6.2×10^{-6}
SJ-3	22.5	4.49	5.01	18.6	1.78×10^{-3}	3.50×10^{-9}

Table 5 Evaluation sheet of case study for community water supply project.

i) Possible environmental impact

No.	Items of problem	Evaluation	Reason
1	Cessation of artesian conditions	No impact is expected	- No spring
2	Head loss due to mutual interference	No impact is expected	- No spring - No existing well
3	Reduction of yield of neighboring well	No impact is expected	- No existing well
4	Land subsidence	No impact is expected	- Basement region
5	Groundwater Pollutions	No impact is expected	- No point of releases
6	Sea water intrusion	No impact is expected	- Basement region, inland

ii) Availability of data (for examination of groundwater balance)

No.	Subsystem of data	Evaluation	Reason
A: Recharge system			
1	Meteorology	Not available	No observatory or no record
2	Hydrology	Not available	No observatory or no record
3	Artificial	Not available	No previous investigation
B: Basin system			
4	Topography	Partly available	Map data only
5	Geology	Partly available	Map data only
C: Discharge System			
7	Meteorology and hydrolog	Not available	No observatory or no record

ii) Study scale

No.	Term	Allocated perioc	Determination
1	Optimal yield (1)	5 months	Possible
2	Optimal yield (2)	5 months	Possible
3	Appropriate utilizable yield	5 months	Possible
4	Optimal critical discharge	5 months	Possible
5	Safe yield	5 months	Impossible
6	Perennial yield	5 months	Impossible
7	Sustained yield	5 months	Impossible
8	Mining yield	5 months	Impossible
9	Permissible yield	5 months	Impossible

iv) Management level

No.	Items	Management level
A: System management		
1	Operation	Community of inhabitant
2	Maintenance	Community of inhabitant
B: Groundwater basin management		
3	Monitoring	District council
4	Analysis and evaluation	District council
5	Overall management	District or village

results obtained by the study, the risks due to environmental problems are negligible. Since there are no existing tube wells that exploit deeper aquifers, the risks for problems directly caused by the decline of groundwater can also be treated as negligible.

ii) Availability of data, especially meteorological and hydrological data, is very poor. The period allocated for the study was only 5 months because of urgent programs being carried out to relieve drought damage. The management level is district, since there is only one hand pump well in a village. Thus, it is impossible to apply the concept of basin yield.

iii) For the community water supply project, the concept of basin yield is not required considering the urgency of the project and lack of environmental impact. The terms of optimal yield (1) and (2), appropriate utilizable yield, and optimum critical discharge are the concepts, which can be adopted for the project.

The determined concepts however, are not universally valid for the province. It is required to review the pumping rate for the operation, in accordance with the progress of the groundwater development and urban planning of the province.

Case study-2, Rural water supply project

Project digest

The project selected for the case study of rural water supply project is "IKK System Water Supply Project in East Java" in the Republic of Indonesia (JICA 1992). In Indonesia, the provision of water supply system for the entire nation is given high priority in the national development plan (National Development Planning Agency, 1991). Based on this policy, public water supply systems for rural towns, which have no access to safe water, were planned by the project. The project constructed public tap water supply systems in 30 selected rural towns. The water sources of these systems are groundwater. Three typical towns are shown on the hydrogeological map in Fig. 7.

Hydrogeological study

Electric explorations using the Schlumberger electrode configuration method were carried out to examine the hydrogeological structure of each project site. The project sites are located on coastal plain fronting onto the Java Sea. The geology of the area is young Quaternary volcanic products overlain by alluvial deposits. Estimated hydrogeological conditions by the resistivity profiles and borehole logs of the area are summarized below.

i) Besk (See, Fig. 8)

The profile was analyzed as a 5 layered model. A thin Alluvial deposit is detected at the top layer in the area. The resistivity of the layer is very low, ranging from 8 to 21 ohm-m. Three formations under the Alluvial deposit are estimated as Quaternary volcanic products. Among these, 2nd and 4th layers are expected as the aquifer from the interpretation of the resistivity value. The 5th layer is interpreted as the basement of the groundwater basin. A test well ET-2 having its screen pipes at depths from 106 to 134 m, to extract the groundwater in the aquifer of the 4th layer, was drilled in the location between Station Nos. BS-7 and BS-8. An existing well is located near Station No. BS-10. A borehole log is not recorded for the well. However, the well is considered to be the same as the aquifer for test well ET-2 based on the depth of well of 135m.

ii) Maron (See, Fig. 9)

In this profile, a 7 layered model was applied. The main formations consist of Alluvial deposits in the surface layer (1st and 2nd layer), Quaternary volcanic deposit in middle of the sequence (3rd, 4th, 5th and 6th layer), and Tertiary basement rock in the bottom layer (7th layer). Based on the resistivity ranges analyzed, 2 layers of 4th and 6th are expected as aquifers. A test well CT-5 was drilled at Station MR-7 to extract the groundwater in the aquifer of the 6th layer. An existing well GT-2 is located near Station MR-5.

iii) Geding (See, Fig. 10))

The profile was analyzed as a 6 layered model. The thin Alluvial deposit is detected at the surface 2 layers of the sequence. The resistivity of these layers is low, ranging from 9 to 38 ohm-m. Four layers (3rd, 4th, 5th and 6th layer) are estimated as Quaternary volcanic deposits. Among these layers, the 3rd layer is expected as an aquifer. The location of a test well CT-6 was placed at Station GE-7. No existing wells had been drilled in the surroundings.

Pumping Test

Fig. 11 shows the results of the constant discharge test and recovery test at ET-2 and CT-5 test wells, with the water level variation of existing wells BT-1 and GT-2. The obtained aquifer properties of each well are summarized in Table 6.

In the Besk area, the static water level of a pumped well ET-2 is measured as 8.08 m.bgl, and in the observation well BT-1 as 10.12 m.bgl. The difference of the 2.04 m in those static water levels is due to the difference of ground elevation. The drawdown of the water level in observation well BT-1 was observed after 240 minutes after the commencement of pumping at a pumped well ET-2 (See, Chart 11a). The maximum drawdown of the water level was measured as 0.11 m.bgl after 2,880 minutes of pumping elapsed time. The recovery of the water level was detected after stopping the pumping of ET-2 pumped well.

A similar phenomenon was also observed in the project site of Maron. In the area, the static water level of a pumped well CT-5 was measured as 13.80 m.bgl, and in an observation well GT-2 as 15.99 m.bgl. The difference of the 2.19 m in those static water levels is due to the difference of ground elevation. The drawdown of the water level in observation well GT-2 was observed after 540 minutes of the commencement of pumping at a pumped well CT-5 (See, Chart 11b). The maximum drawdown of the water level was measured as 0.59 m.bgl after 2,880 minutes of pumping elapsed

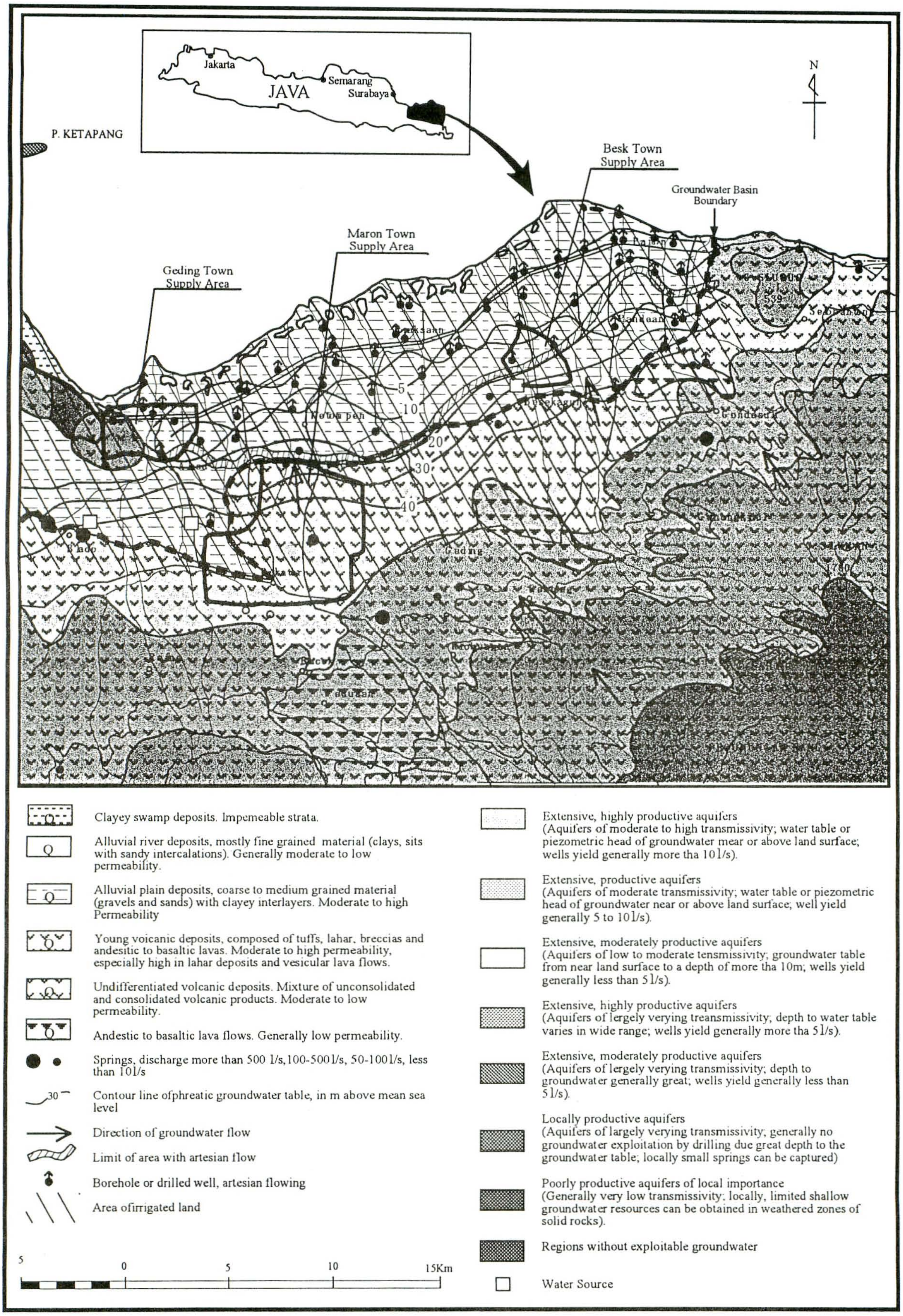
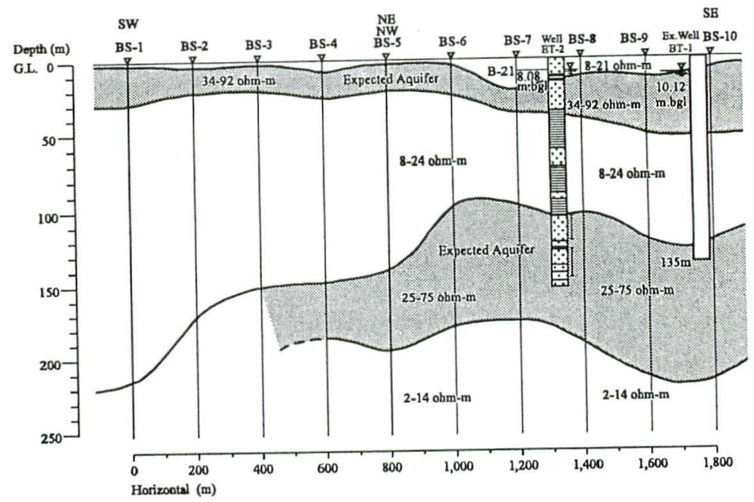
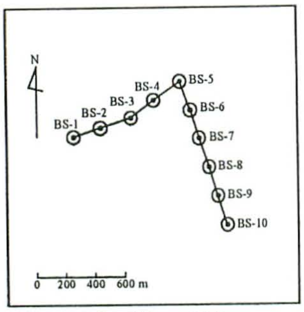


Fig. 7 The project location of IKK water supply project shown on the hydrogeological map of East Java of Republic of Indonesia. After JICA (1992), modified by Hata.





Location of Survey Stations

Layer	Resistivity Range (ohm-m)	Estimated Lithology	Remarks (Lithology)
1	8 − 21	Sand, Clay	Alluvial Depo.
2	34 ··· 92	Sand	Quat. Volcanic
3	8 − 24	Clay, Clayey sand	Quat. Volcanic
4	25 ··· 75	Sand, Clayey sand	Quat. Volcanic
5	2 − 14	Tuff, Mudstone	Tert. Volcanic

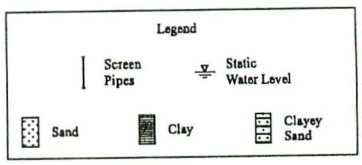
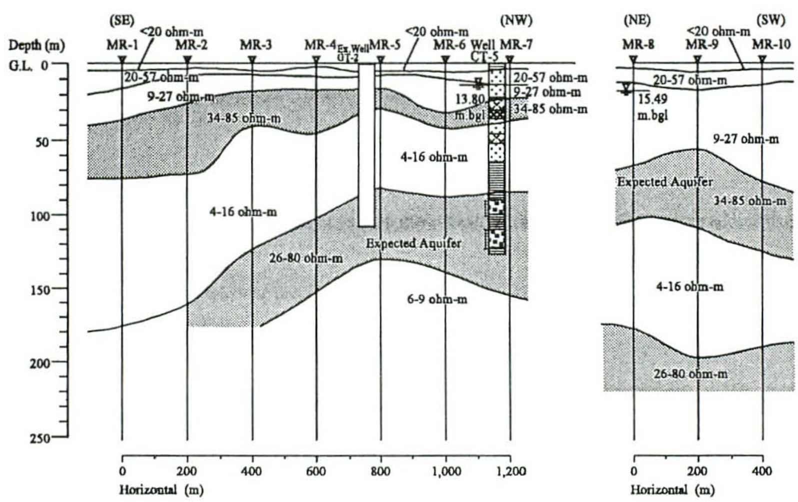
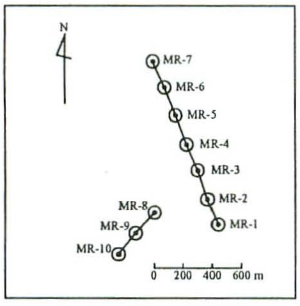


Fig. 8 Resistivity profile of Besk, station No. BS-1 to 10.





Location of Survey Stations

Layer	Resistivity Range (ohm-m)	Estimated Lithology	Remarks (Lithology)
1	< 20	Surface soil	Surface soil
2	20 − 57	Sand	Alluvial Depo.
3	9 − 27	Clayey sand	Quat. Volcanic
4	34 − 85	Tuffaceous sand, Tuffaceous clay	Quat. Volcanic
5	4 − 16	Alternation of sand and clay	Quat. Volcanic
6	26 ··· 80	Alternation of sandstone, breccia and clay	Quat. Volcanic
7	6 − 9	Sandstone	Kabuh Form.

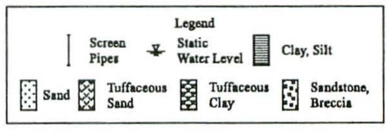
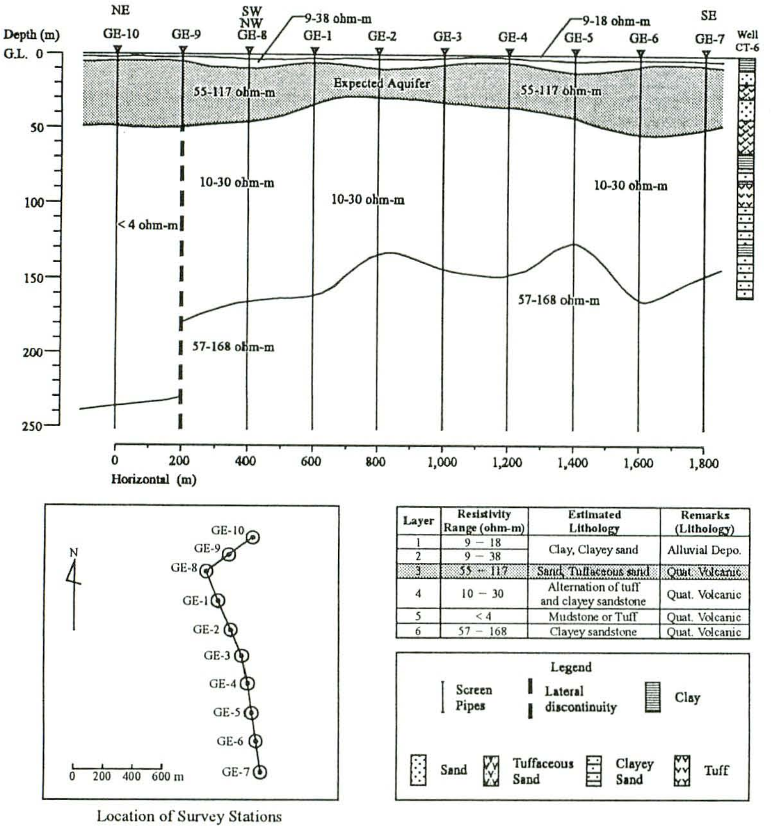


Fig. 9 Resistivity profile of Maron, station No. MR-1 to 10.



Layer	Resistivity Range (ohm-m)	Estimated Lithology	Remarks (Lithology)
1	9 – 18	Clay, Clayey sand	Alluvial Depo.
2	9 – 38		
3	55 – 117	Sand, Tuffaceous sand	Quat. Volcanic
4	10 – 30	Alternation of tuff and clayey sandstone	Quat. Volcanic
5	< 4	Mudstone or Tuff	Quat. Volcanic
6	57 – 168	Clayey sandstone	Quat. Volcanic

Fig. 10 Resistivity profile of Geding, station No. GE-1 to 10.

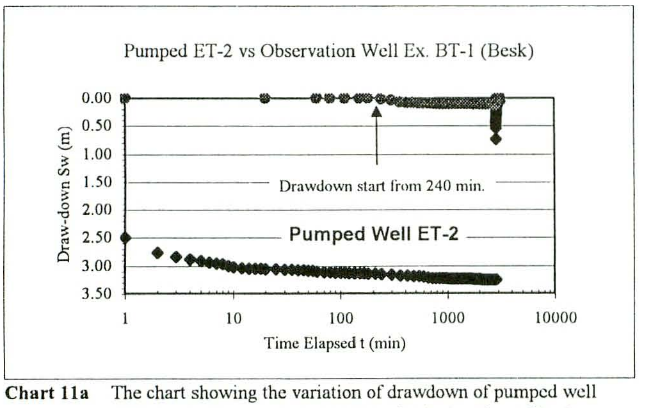


Chart 11a The chart showing the variation of drawdown of pumped well (ET-2) and observation well (BT-1) in the location of Besk.

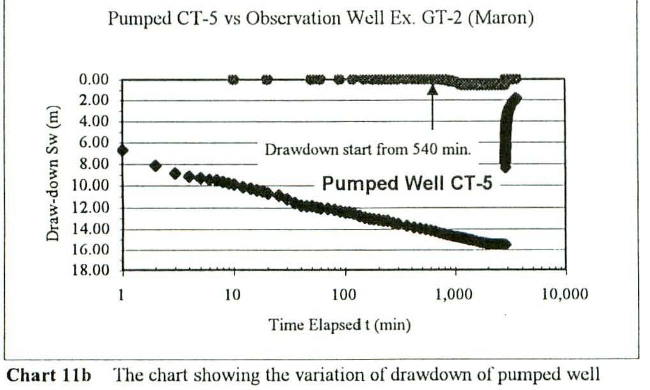


Chart 11b The chart showing the variation of drawdown of pumped well (CT-5) and observation well (GT-2) in the location of Maron.

Fig. 11 Interaction between the pumped wells and existing wells, East Java of Republic of Indonesia.

Table 6 Aquifer properties of test wells ET-2 and CT-5 in the East Java, Republic of Indonesia.

Well No.	Pumping Rate (l/min.)	Drawdown (m)	Specific Capacity (l/min./m)	Transmissivity T(m^3/day/m)	Permeability K (cm/sec.)	Storativity S
ET-2	1050	3.25	323.07	808.67	2.60×10^{-2}	2.47×10^{-7}
CT-5	750	15.55	48.23	77.17	2.28×10^{-3}	3.56×10^{-4}

time. The recovery of the water level was also detected after stopping the pumping of CT-5 pumped well.

As a result of these pumping tests, a remarkable variation of the water level was observed in the existing wells at the project sites of Besk and Maron. The influence of the pumping of test wells could be the factor that caused this. Therefore, the potential impact of groundwater problems is suspected, such as head loss due to mutual interference and reduction of yielding of neighboring well.

Since there are no existing wells situated in the project site of Geding, comparison of the water level in the observation and pumped well could not be made. Considering the similarity of the hydrogeological structure of the areas, similar suspected impact can be anticipated.

Examination of an applicable yield concept

Based on the results of the hydrogeological study and the pumping tests carried out, an applicable yield concept for the project is examined. An evaluation sheet to examine an applicable yield concept is shown in Table 7. The results of the case study are summarized below.

i) The aquifer systems of existing wells in use and planned wells by the project are found to be the same. Considering the results obtained by the studies, serious impacts for most of the problems caused by the decline of groundwater level are suspected to be due to the existence of wells in use. Considering the geological condition of Quaternary sediments and coastal plain, the area has a risk of land subsidence and seawater intrusion.

ii) The data required to determine the basin yield is also available. However, further investigations regarding the artificial infiltration system and the basin system are required. These investigations can be carried out within the allocated study period. The management level is municipal. Thus, it is possible to apply the concept of basin yield.

iii) For the rural water supply project, the concept of basin yield must be applied, because serious environmental impacts are suspected. There are many existing water wells and springs in use in the project area. Therefore, the concept of permissible yield among the basin yields is essential to determine the extractable groundwater yield for the project.

Case study-3, Regional groundwater development

Project digest

The project selected for the case study of regional groundwater development is "The study on the Development of Water Resources in Northern Chile" in the Republic of Chile (JICA 1995). The increasing population in the future will further worsen the circumstances of the water supply in the cities of the region. The project has therefore, studied regional groundwater potential to formulate a development plan of the water resources in the area to cope with increased water demand due to rapid urbanization. The hydrogeological map of the area is shown in Fig. 12.

Hydrogeological study

There are many wells that have been drilled for the water supply and geological survey purposes. Among these wells, borehole logs are available only for deep tube wells Nos. 180, 189, 951p, 234, 316, 141, 420p, 432 and 450. The other wells are shallow and for private use. No technical data are recorded. Under the project, a total of 7 test wells (J-3, J-4, J-C, J-D, J-5, J-E, J-7, J-8 and J-F) were also drilled to evaluate the hydrogeological structure. Using the geological logs of such wells, a geological profile is provided as shown in Fig. 13. The locations of the profile and the wells are shown in Fig. 12. The aquifer exists in Altos de Pica Formation of the Quaternary deposits. The Altos de Pica Formation consists of a total of 4 units (Q4, Q3, Q2, and Q1). Unit Q4, consisting of sand and gravel with mud, is lenticularly distributed over the whole aquifer area. No impermeable layers are identified between units Q4 and Q3. The most demanding aquifers appear in units Q4 and Q3. These units are underlain by the impermeable clay bed of Q2.

Monitoring of the groundwater level

Since 1981, the static water level has been measured almost every month by the local government on the selected wells. The results of the measurements are shown in Figs. 14 and 15. The data shows irregularly

Table 7 Evaluation sheet of case study for rural water supply project.

i) Possible environmental impact			
No.	Items of problem	Evaluation	Reason
1	Cessation of artesian conditions	Serious impact is expected	- Artesian wells in use - Springs in use
2	Head loss due to mutual interference	Serious impact is expected	- Springs and existing wells in the same aquifer
3	Reduction of yield of neighboring well	Serious impact is expected	- many existing wells
4	Land subsidence	Serious impact is expected	- Quaternary sediment
5	Groundwater pollution	Partly some impact is expected	- Landfill points of waste
6	Sea water intrusion	Serious impact is expected	- Coastal plain

ii) Availability of data (for examination of groundwater balance)			
No.	Subsystem of data	Evaluation	Reason
A: Recharge system			
1	Meteorology	Available	Observatory system exists
2	Hydrology	Available	Observatory system exists
3	Artificial	Not available	No previous investigation
B: Basin system			
4	Topography	Partly available	Map data only
5	Geology	Available	Geological and hydrogeological map
C: Discharge system			
7	Meteorology and hydrolog	Available	Observatory system exists

iii) Study scale			
No.	Term	Allocated period	Determination
1	Optimal yield (1)	15 months	Possible
2	Optimal yield (2)	15 months	Possible
3	Appropriate utilizable yield	15 months	Possible
4	Optimal critical discharge	15 months	Possible
5	Safe yield	15 months	Possible (to some degree)
6	Perennial yield	15 months	Possible (to some degree)
7	Sustained yield	15 months	Possible (to some degree)
8	Mining yield	15 months	Possible (to some degree)
9	Permissible yield	15 months	Possible (to some degree)

iv) Management level		
No.	Items	Management level
A: System management		
1	Operation	Municipal water supply department
2	Maintenance	Municipal water supply department
B: Groundwater basin management		
3	Monitoring	Municipal water supply department
4	Analysis and evaluation	Prefecture branch office of central geological institute
5	Overall management	Prefecture branch office of central geological institute

low static water level at Wells Nos. 316, 180 and 234 during the period of 1998 to 1990, due to the pumping of neighboring wells. The other minor fluctuation could be considered as measurement error. As shown in these figures, the static water level in the basin has gradually declined. In the northern part of the basin, the range of the declining rate is estimated as 0.03 to 0.12 m/year, while the southern part of the basin shows a slightly broader range of 0.09 to 0.36 m/year. The static water level of well No.316 located in the central basin shows the highest declining rate of 0.36 m/year. This is because many dense wells are located in and around this area.

Examination of an applicable yield concept

Based on the results of the hydrogeological study and the monitoring of the groundwater level, an applicable yield concept for the project is examined. An evaluation sheet to examine an applicable yield concept is shown in Table 8. The results of the case study are summarized below.

i) The decline of groundwater level in the area has already commenced and was so detected. Serious impact is suspected for most of the problems for declining of groundwater level due to further groundwater development. Considering the geological condition of Quaternary Alluvial deposits, the area also has the risks of land subsidence and groundwater pollution.

ii) The data required to determine the basin yield is available. However, further investigation regarding the artificial infiltration system and basin system are required. Since the allocated study period is long, the required investigations can be carried out. The man-

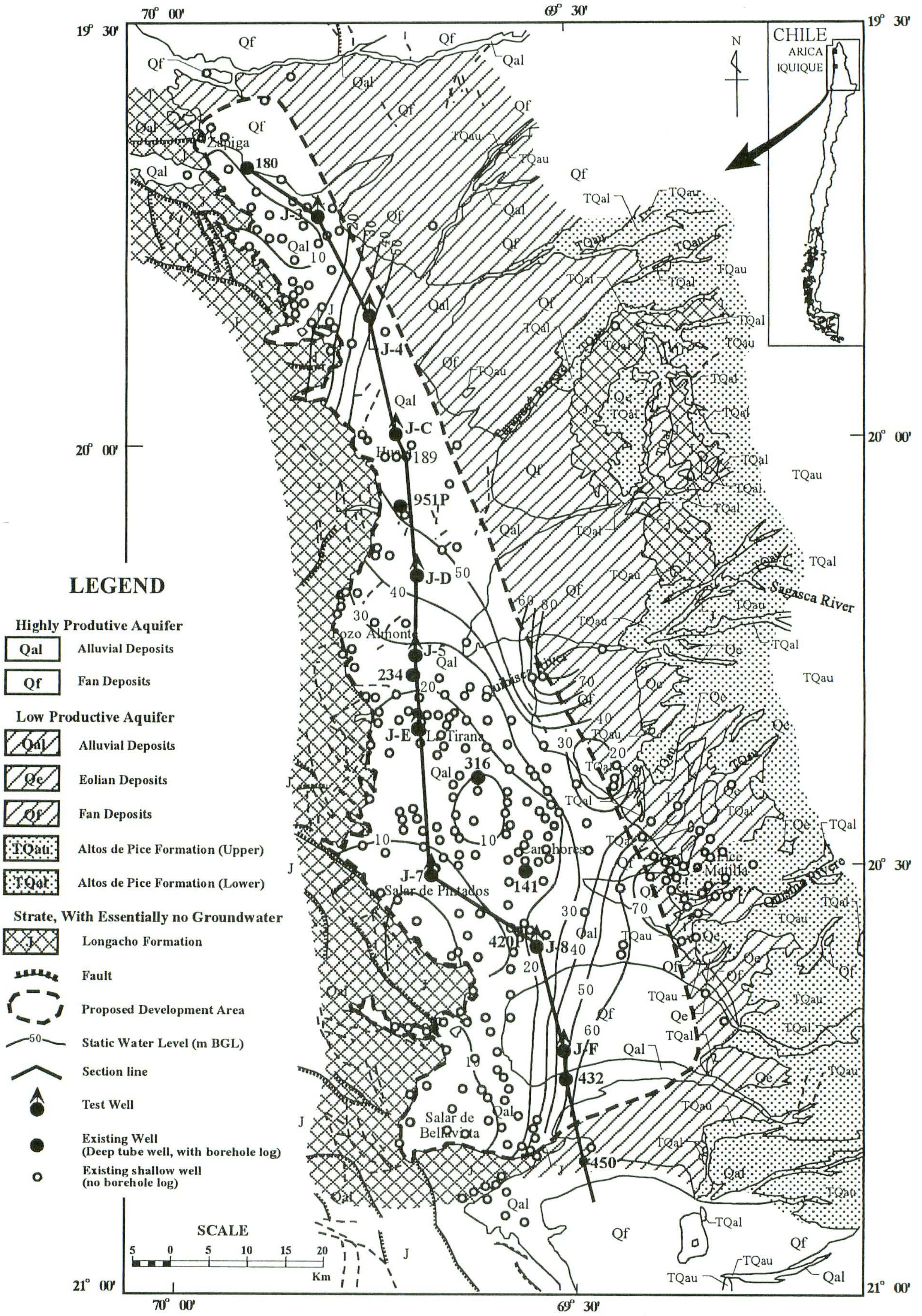


Fig. 12 Hydrogeological map of Pampa del Tamarugal basin of the Republic of Chile. After JICA (1995), modified by Hata.

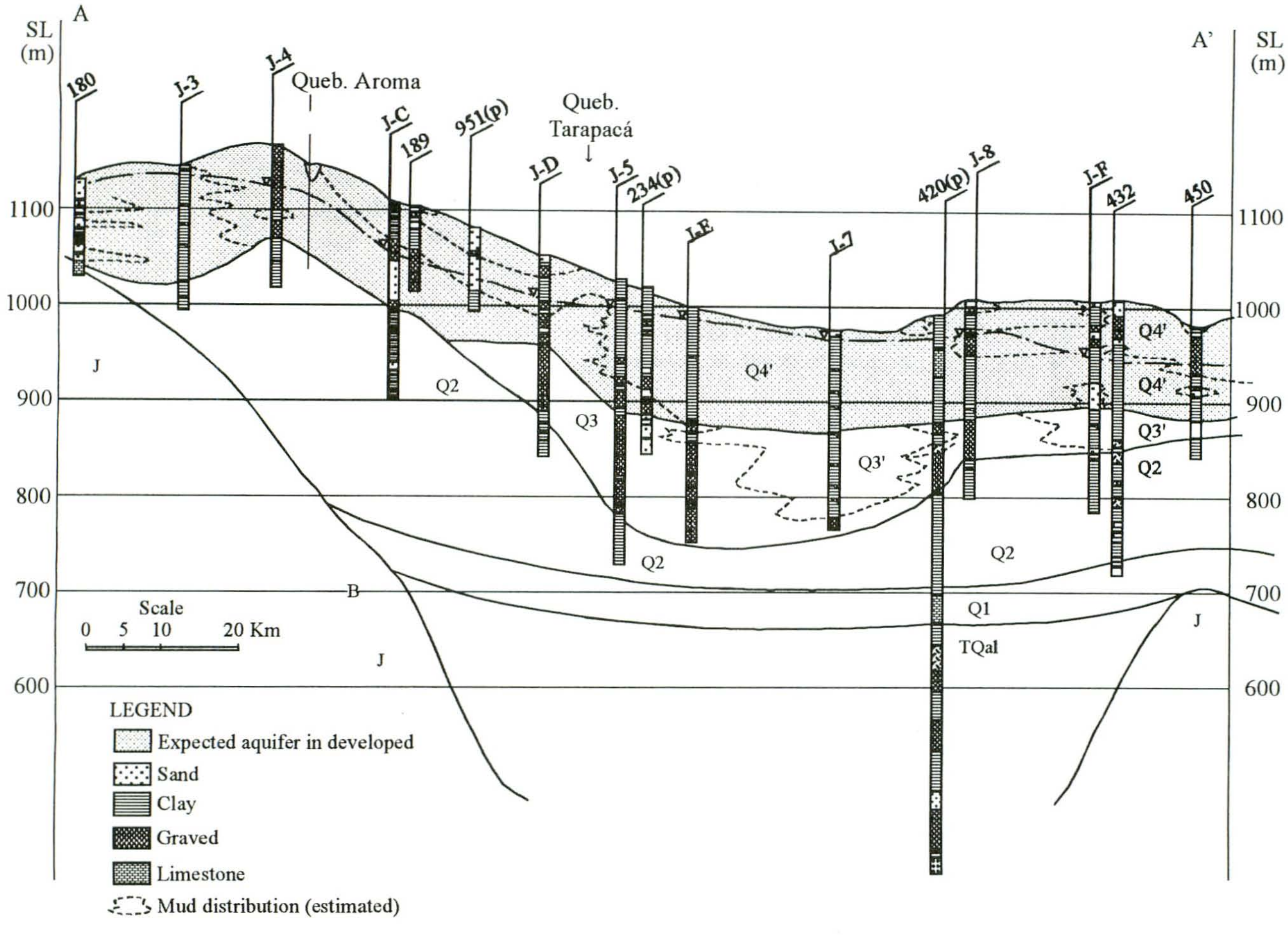


Fig. 13 Geological profile of Pampa del Tamarugal basin.

agement level is municipal. Thus, it is possible to apply the concept of "basin yield" including permissible yield.

iii) For this study, the concept of basin yield must be applied, because serious environmental impact is expected. Furthermore, as the project is part of the water source for municipal water supply systems, the potential under the condition of permissible level, namely permissible yield must be determined.

Discussion

The case studies shown in the previous sections, demonstrate that the application of the groundwater yield concept for the estimation of extractable groundwater must differ in projects. Consideration must be made to propose a definitive approach to examinations based on the practical stages of the project.

In the planning stage, a master plan for the groundwater development is normally formulated based on the water demand and source potential. Subsequently in the study stage, a feasibility study is normally made to select a priority project or to decide project implementation. Therefore, the essential determination for proper groundwater development and use (that is, an appropriate yield concept and permissible level of development) should be determined in the planning and study stages. A proposed flow chart for determination of appropriate groundwater yield concept and permissible level of development is shown in Fig. 16.

Master Plan

An appropriate yield concept for the project should be determined in the master plan stage. Based on the results of investigations, the estimation of source potential and water demand are normally made at this stage. In the planning stage, hydrogeological study will normally be carried out to examine the source availability. In addition, if the results of the study suggest the insufficiency of the potential and/or changes of the water quality, the design policy must be reviewed. Factors for further examination that must be made in the next step are: 1) possible environmental impact, 2) groundwater balance, 3) study period and 4) management level.

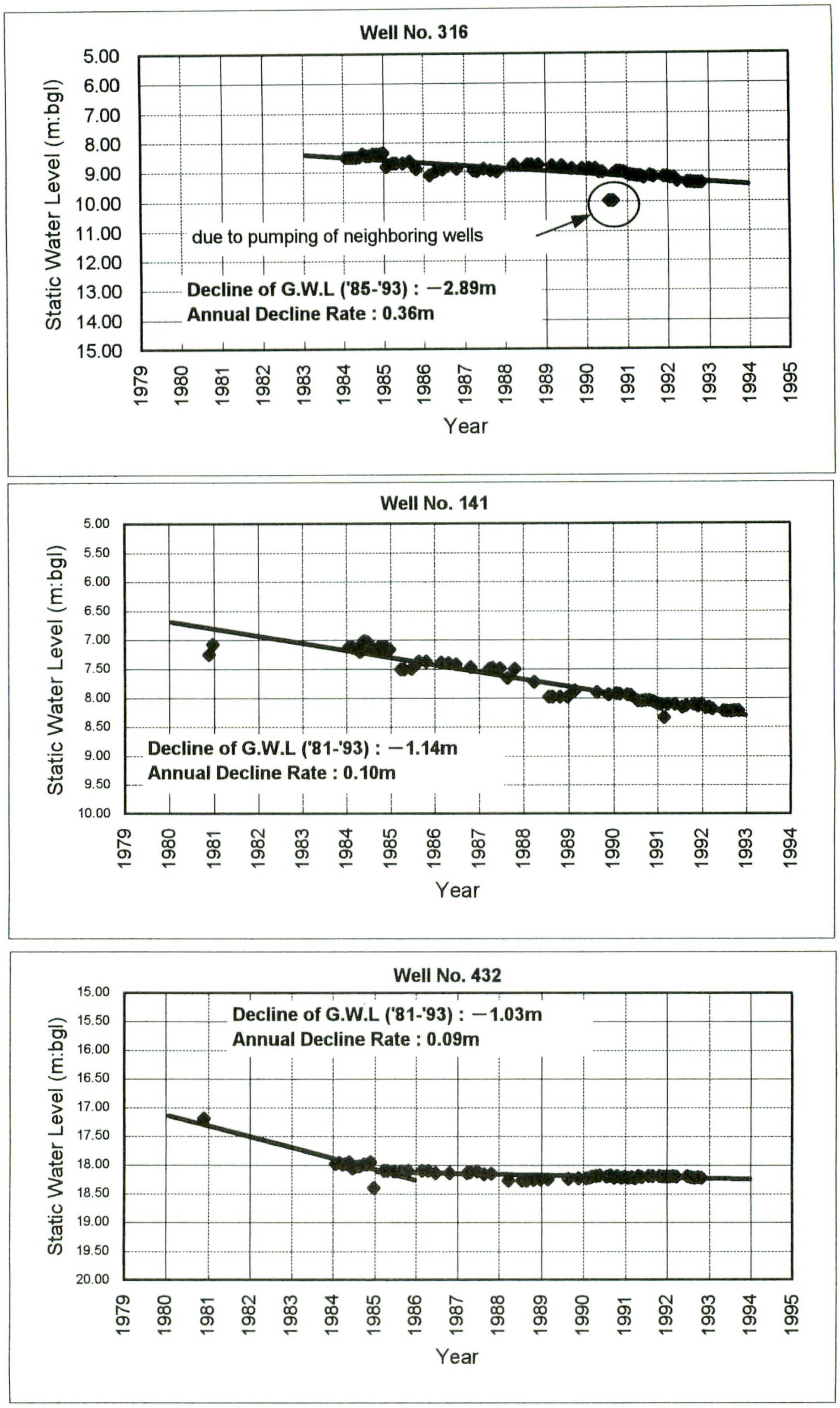


Fig. 14 Historical variation of the static water levels in the well No. 180, 951 and 234, located in the southern part of the Pampa del Tamarugal Basin.

Based on such examination and collation with the master plan, an appropriate yield concept must be selected. Furthermore, if the yield estimated by an appropriate yield concept shows insufficiency of the required amount, the master plan must be reviewed. If it is concluded that the consideration of basin yield is not

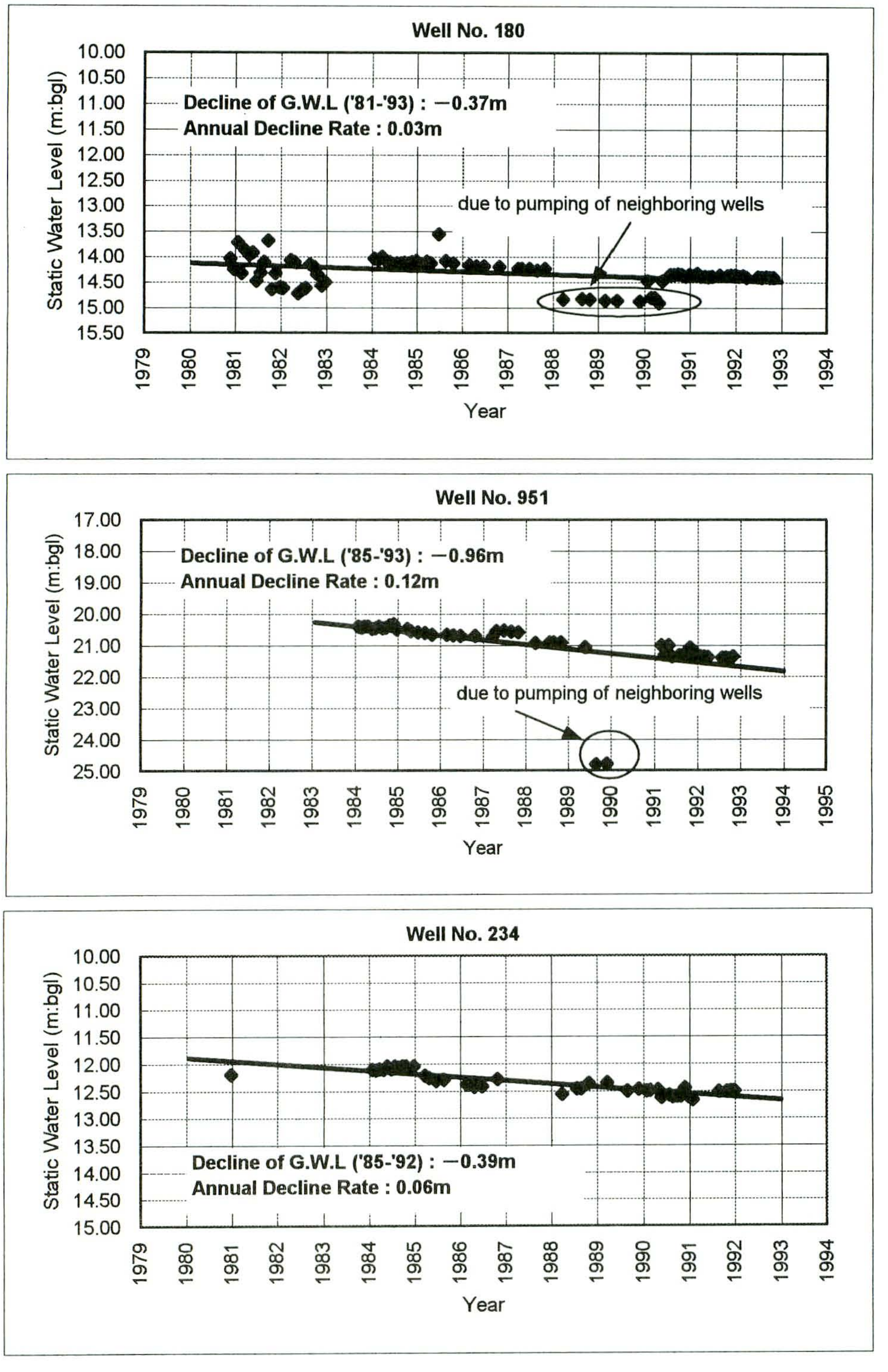


Fig. 15 Historical variation of the static water levels in the well No. 316, 141 and 432, located in the northern part of the Pampa del Tamarugal Basin.

required, and if the project requires urgent implementation due to basic human needs, basic design can be started after the planning stage.

Feasibility Study

In the master plan, if it is decided that the concept of basin yield should be applied as a proper concept for project implementation, the extractable yield should be estimated in the study stage. The planner tends to consider the groundwater as an immense reservoir. In fact, however, only a certain amount of water can be withdrawn without adversely affecting the quantity and qual-

Table 8 Evaluation sheet of case study for regional groundwater development.

i) Possible environmental impact			
No.	Items of problem	Evaluation	Reason
1	Cessation of artesian conditions	No impact is expected	- No artesian wells - No springs
2	Head loss due to mutual interference	Serious impact is expected	- Existing wells in use
3	Reduction of yield of neighboring well	Serious impact is expected	- Existing wells in use
4	Land subsidence	Serious impact is expected	- Quaternary sediment
5	Groundwater pollutions	Partly some impact is expected	- Salt lake exist
6	Sea water intrusion	Partly some impact is expected	- Coastal plain

ii) Availability of data (for examination of groundwater balance)			
No.	Subsystem of data	Evaluation	Reason
A: Recharge system			
1	Meteorology	Available	Observatory system exists
2	Hydrology	Available	Observatory system exists
3	Artificial	Not available	No previous investigation
B: Basin system			
4	Topography	Partly available	Map data only
5	Geology	Available	Geological and hydrogeological map
C: Discharge system			
7	Meteorology and hydrolog	Available	Observatory system exists

iii) Study scale			
No.	Term	Allocated period	Determination
1	Optimal yield (1)	24 months	Possible
2	Optimal yield (2)	24 months	Possible
3	Appropriate utilizable yield	24 months	Possible
4	Optimal critical discharge	24 months	Possible
5	Safe yield	24 months	Possible
6	Perennial yield	24 months	Possible
7	Sustained yield	24 months	Possible
8	Mining yield	24 months	Possible
9	Permissible yield	24 months	Possible

iv) Management level		
No.	Items	Management level
A: System management		
1	Operation	Municipal water supply department
2	Maintenance	Municipal water supply department
B: Groundwater basin management		
3	Monitoring	Municipal water supply department
4	Analysis and evaluation	Prefecture branch office of central geological institute
5	Overall management	Prefecture branch office of central geological institute

ity of water (Zaporozec 1983). This amount should be determined by the characteristics of the environment in which groundwater occurs and by the interaction of groundwater with precipitation, surface water, and people. Therefore, the determination of permissible level for the development and conservation of groundwater must be made. Such determination must be based not just on hydraulic estimation, but on consideration of the following: 1) socioeconomic conditions, 2) environmental impact, 3) water balance and 4) groundwater potential. These considerations are essential for the appropriate groundwater development and use.

Conclusion

For groundwater development projects, various concepts of the extractable groundwater yield have been utilized. The application of such concepts for the practical projects both inside and outside Japan, however, has been confused. As a result, for example in Japan's past, groundwater problems such as land subsidence and oxygen deficiency in underground space air, occurred in industrial areas of Tokyo and Osaka (Research Group for Water Balance, 1995). The author suggests that the main reason for this confusion is due to the inaccurate classification of the dimension (scale of water source)

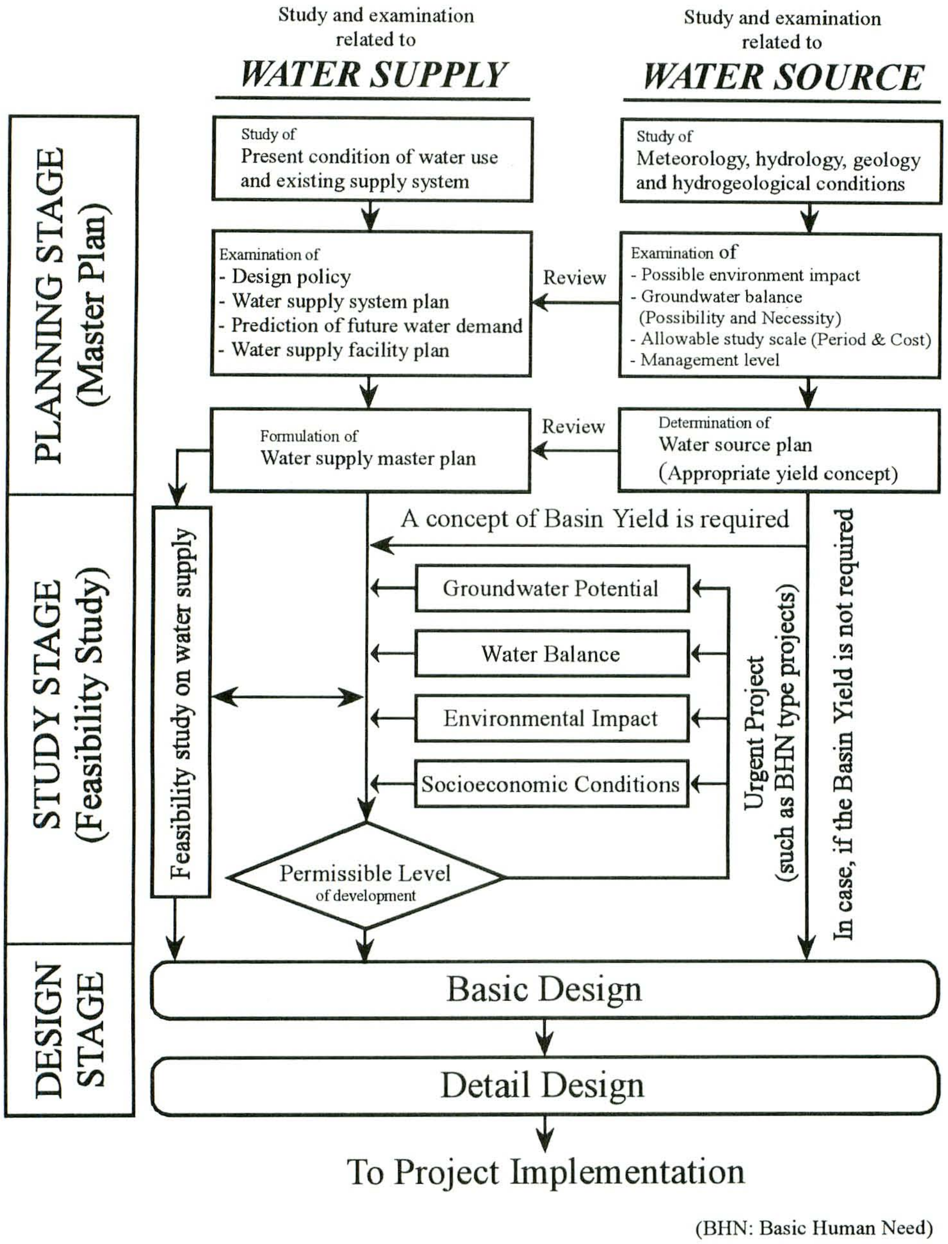


Fig. 16 Flow chart of determination of appropriate groundwater yield concept.

of "well yield", "aquifer yield" and "basin yield" for the application of the concepts.

In this paper, the concepts of the extractable groundwater yield have been classified based on the differences of the dimension by review of existing literature both domestic and foreign.

Based on these results, estimation methods for extractable yield of groundwater were established. The established methods by this study are as follows:

1) To understand the characteristics of each concept of extractable groundwater yield.

2) To utilize the concepts by the classified dimension of "well yield", "aquifer yield" and "basin yield" in applying the concepts.

3) To use the concepts in accordance with the project scale.

4) To determine a concept to be applied, based on the examination of four parameters, in the planning stage of the project: namely, possible environmental impact, groundwater balance, study period and management level.

5) To examine the extractable groundwater yield, based not just on hydrological calculation, but on consideration of four factors in the study stage of the project: namely, socioeconomic conditions, environmental impact, water balance and groundwater potential.

6) With the practical risks that might arise on the project area in mind, to determine the "permissible yield" of groundwater by comparing and evaluating the advantage derived from the pumpage of groundwater, risks of environmental problems and socioeconomic contribution of the project.

7) To review the determined extractable yield of groundwater in accordance with the progress of the groundwater development and urban planning of the project area.

Acknowledgments

The author expresses his deep thanks to Prof. Dr. Hisao KUMAI of Osaka City University for his continuing guidance and encouragement, critical reading of the manuscript and many valuable comments. The author would also like to thank Prof. Dr. Koichi NAKAGAWA and Associate Prof. Dr. Muneki MITAMURA of Osaka City University for their useful suggestions and critical reading of the manuscript. The author also acknowledges the constructive reviews by Dr. Naoaki Shibasaki of Kokusai Kogyo Co., LTD., to improve the manuscript. The author is also grateful to Japan International Cooperation Agency (JICA) for their kind permission to use valuable data to present this paper.

References

Asia Arsenic Network (AAN), Research Group for Applied Geology (RGAG) and Department of Occupational & Environmental Health, National Institute of Preventive & Social Medicine, Bangladesh (NIPSOM) (1999) Arsenic Contamination of Groundwater in Bangladesh, Interim Report of the Research at Samta Village, AAN, RGAG & NIPSOM Publ., Tokyo, 90 pp.

American Geophysical Union (AGU) (1978) Groundwater Modeling Assessment Project Steering Committee (SCOPE), Numerical models in groundwater resource management. Center for Environmental Information Science, Tokyo, 121pp.

American Society of Civil Engineers (1961) Groundwater management. Manuals and reports on engineering practice, ASCE no. 40, 36-40.

Gao C. (1997) The geological setting of arsenic contamination in Inner Mongolia, China. The special issue of "Chigaku-Kyoiku to Kagaku-Undo", The Association for the Geological Collaboration in Japan, 28-33.*

Hata Y. (1998) Review and evaluation of previous concepts and methods for the determination of extractable groundwater yield. Earth Science, vol. 52 no.4, 251-261.

Hata Y. (1999) Actual circumstances and problems on the determination of groundwater yield for the groundwater development project in the developing countries. Earth Science, vol. 53 no.3, 190-201.

Hata Y. (2000) Study on the permissible limit of groundwater development in developing countries. Technology & Development (Kokusai Kyouryoku Kenkyuu) JICA vol. 16 no.1, 59-68.**

Hata Y. (2001) Study on the concepts of extractable groundwater yield for the groundwater development project. Earth Science, vol. 55 no. 1, 37-50.

Japan Groundwater Technology Association (JGTA) (1962) A series of laws on regulation for groundwater extraction. JGTA, Tokyo, 69pp.*

Japan Institute of Construction Engineering (JICE) (1993) Guideline for investigation and observation of groundwater, under the editorial supervision of River Bureau, Ministry of Construction. Sankai-do, Tokyo, 330pp.*

Japan International Cooperation Agency (JICA) (1988) Basic design study on groundwater development project (Phase-II) in Southern Province in the Republic of Zambia. Final report, JICA, Tokyo, 260pp.

Japan International Cooperation Agency (JICA) (1992) The study on IKK system water supply project in province of Central Java, East Java and Bali, The Republic of Indonesia. Supporting report C, JICA, Tokyo, 121pp.

Japan International Cooperation Agency (JICA) (1995) The study on the development of water resources in northern Chile. Main report, JICA, Tokyo, VII-37pp.

Japan Water Works Association (JWWA) (1990) A guideline for design of water supply facilities, under the editorial supervision of Ministry of Health and Welfare. JWWA, Tokyo, 715pp.

Kurata N. (1960) Groundwater development and land subsidence. Rikou-Tosho, Tokyo, 127pp.*

Lee C.H. (1915) The determination of safe yield of underground reservoirs of the Closed Basin Type. Trance ASCE, vol. 78, 148-151.

Ministry of International Trade and Industry (1965) The study on appropriate use for groundwater. Ministry of International Trade and Industry, Tokyo, 59pp.*

Murashita T. (1962) Groundwater hydrology. Shoko-do, Tokyo, 211pp.*

National Development Planning Agency (1991) Five year national development plan in 4th. NDPA, Government of Indonesia, Jakarta, 679pp.

National Water Well Association of Japan (NWWA) (1993) Estimation Standard for Water Well Drilling. NWWA, Tokyo, 124pp.*

Research Group for Water Balance (1995) Environmental management of groundwater basin in Japan. Jour. Geol. Soc. Japan, vol. 101, 783-794.

Shibasaki N. (1997) Geologic problems of arsenic groundwater contamination in Bangladesh. The special issue of "Chigaku-Kyoiku to Kagaku-Undo", The Association for the Geological Collaboration in Japan, 34-43.*

Shibasaki T. and Kumai H. (1968) Hydrologic balance in confined groundwater basin. Jour. Geol. Soc. Japan, vol. 74, 165-176.

Shibasaki T. (1976) Groundwater Basin Management. Tokai Univ. Press., Tokyo, 242pp.*

Shibasaki T. and Research Group for Water Balance (1995) Environmental Management of Groundwater Basins. Tokai Univ. Press., Tokyo, 202pp.

Todd D.K. (1976) Groundwater hydrology second edition. John Wiley & Sons, New York, 535pp.

Zaporozec A. (1983) Human interactions with groundwater. GeoJournal, Wisconsin, vol.7, no.5, 427-433.

* : in Japanese

** : in Japanese with English abstract

Manuscript received April 1, 2002.
Revised manuscript accepted February 3, 2003.