6. Observation of the water storage state by the subsurface dam

Unlike a surface dam, a subsurface dam does not allow direct observation of water storage. It can only be estimated from the groundwater level observed using facilities set up for this purpose.

This chapter describes the observation of groundwater level and other parameters carried out during this project, as well as the water storage state estimated from the results of the observations.

6-1 Facilities for observation of water storage state (facilities for groundwater observation)

Table 6.1 shows the features of the facilities for the observation of the water storage state (facilities for groundwater observation) set up in this project. The distribution of these facilities is shown in Fig. 6.1.

Five of these facilities were equipped with hand pumps for water supply to the villagers (3 pumps of which were still active in March 2003).

(1) Observation wells of the all-strainer type
This is an observation well formed using a plastic pipe with strainers (screens allowing the inflow of water) over all its length deeper than the 5.5 m below the ground surface, installed in a borehole (Fig.6.2-A).

Before the construction of the subsurface dam, 5 wells of this type with automatic water level recorders were installed at the dam site and points on its extension to carry out continuous observation of the groundwater level. After these wells were removed for the construction of the dam, 9 wells of the same type were set up again, 4 of which were across the fossil valley about 200 m upstream of the dam and the rest of which were set up at other places. Five of these wells were equipped with automatic water level recorders.

(2) Large-diameter wells
This is a dug large-diameter well (internal diameter is 1.8 m) whose structure is similar to those prevailing as water-supply facilities in Burkina Faso. In this project, the height of the rim of the well was set at 2 m above the ground surface, and the rim was surrounded by concrete to protect the well from river floods.

At about 100 m upstream and about 50 m downstream of the subsurface dam, “large-diameter wells” (OW-1, -2) were respectively installed for visual and comparative observation of the water storage state by the subsurface dam. On the reservoir area of the “small-scale surface dam with water gates” (see Section 7.(3)), 4 “large-diameter wells” (NP-1 to 4) were also installed for observation purposes. The water-pumping wells set up as a part of the “water-pumping station operated by solar energy” (see Section 7.(1)) were of the same type.

(3) Sets of piezometers of different depths
When there is perched water above the "main" groundwater, the “observation wells of the all-strainer type” mentioned above do not show correctly the “main” groundwater level because of the significant influence of the perched water. The presence of such perched water around the subsurface dam site of this project was suggested by observation during the

excavation and the subsequent observation of groundwater using “wells of the all-strainer type”. To examine the presence of perched water and to observe the “main” groundwater level, sets of piezometers, whose structure is shown in Fig. 6.2-B, were installed at 4 points (PA to PD).

This is an installation consisting of 4 plastic pipes, each of which has a strainer only at its bottom end, and is buried at different depths from each other. The water level in each pipe reflects the level (and the pressure) of the groundwater at the depth of its bottom end.

Table 6.1: Features of the facilities for groundwater observation set up in this project

Type	Number of observation points		Depth to bottom	Distance from subsurface dam	Observation method	Observation period (years)*	Notes
Observation wells of all-strainer type	B-2-3		15 m	At the subsurface dam site	Continuous observation by an automatic water level recorder	From October 1996 to November 1997	Removed with the start of construction of the subsurface dam
	B-2-4		15 m				
	B-2-5		30 m				
	B-2-6		15 m				
	B-2-7		20 m				
	B-U-1		20 m	About 3.5 km upstream	**Automatic recorder**	1997-2003	The recorder was removed in 2002.
	P-1		20 m	About 1.2 km upstream	**Automatic recorder**	1998-2003	The recorder was removed in 2002.
	P-2		20 m	About 650 m upstream	Manual sounder	2001-2003	
	P-3		20 m	About 200 m upstream	Manual sounder	1997-2003	
	P-4		20 m	About 200 m upstream	**Automatic recorder**	1998-2003	The recorder was removed in 2002.
	P-5		20 m	About 200 m upstream	**Automatic recorder**	1998-2003	The recorder was removed in 2002.
	P-6		20 m	About 200 m upstream	Manual sounder	1997-2003	
	P-7		60 m	About 200 m upstream	Manual sounder	1998-2003	A hand pump was installed.
	P-8		20 m	About 400 m downstream	**Automatic recorder**	1998-2003	The recorder was removed in 2002.
Wells of large diameter	NP-1		8 m	About 5 km upstream	Manual sounder	2000-2003	A hand pump was installed.
	NP-2		8 m	About 4 km upstream	Manual sounder	2000-2003	A hand pump was installed.
	NP-3		10 m	About 3.5 km upstream	Manual sounder	2000-2003	A hand pump was installed.
	NP-4		10 m	About 2.5 km upstream	Manual sounder	2000-2003	A hand pump was installed.
	OW-1		10 m	About 100 m upstream	Manual sounder	1998-2003	
	OW-2		9 m	About 50 m downstream	Manual sounder	1998-2003	
	KP-1		20 m	About 150 m upstream	Manual sounder	1998-2003	These were pumping wells for water-supply facilities operated by solar energy. Most of the water levels observed were thus variable.
	KP-2		18 m	About 100 m upstream	Manual sounder	1998-2003	
	KP-3		20 m	About 50 m upstream	Manual sounder	1998-2003	
Sets of piezometers of different depths	PA	1	7.0 m	About 3.5 km upstream	Manual sounder	2000-2003	Installed near B-U-1
		2	4.7 m				
		3	3.0 m				
		4	0.6 m				
	PB	1	5.2 m	About 1.2 km upstream	Manual sounder	2000-2003	Installed near P-1
		2	3.9 m				
		3	2.5 m				
		4	1.0 m				
	PC	1	6.6 m	About 125 m upstream	Manual sounder	2000-2003	Installed between KP-1 and OW-1
		2	4.5 m				
		3	3.1 m				
		4	1.5 m				
	PD	1	6.4 m	About 50 m downstream	Manual sounder	2000-2003	Installed near OW-2
		2	4.8 m				
		3	3.4 m				
		4	0.9 m				

* The end of the observation period of 2003 was February to March.

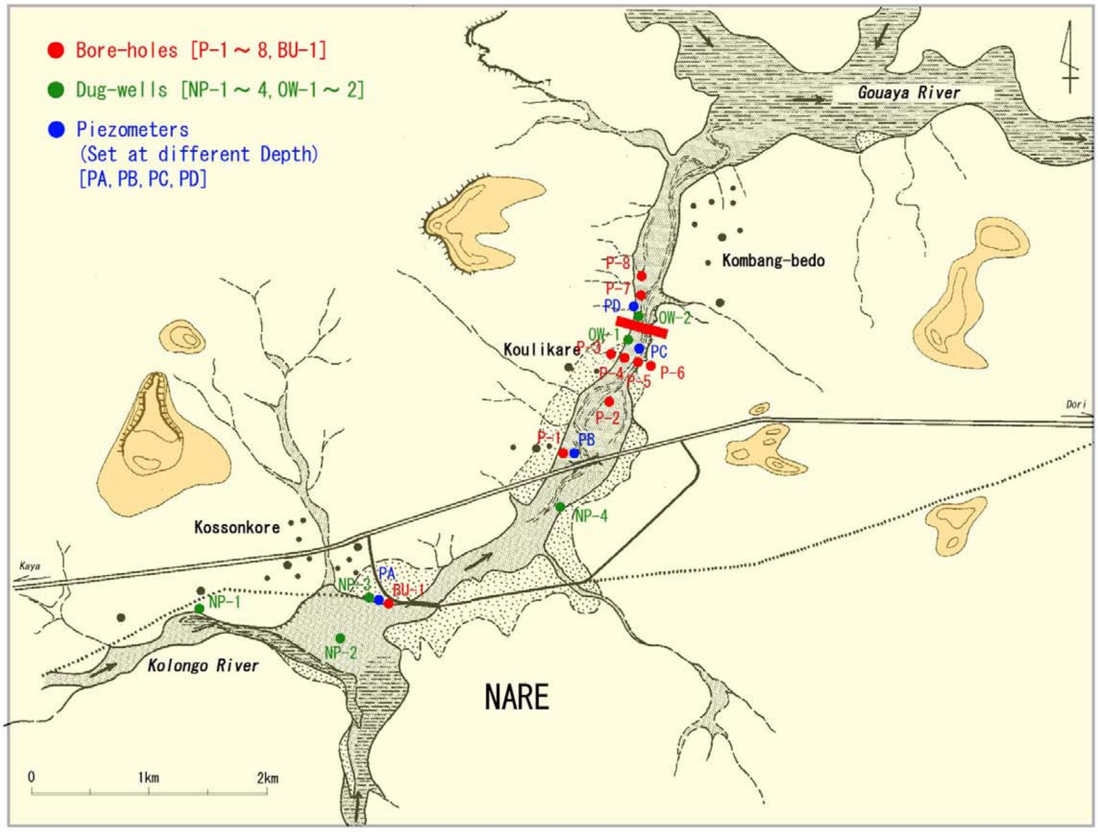


Fig. 6.1: Schematic diagram of the distribution of facilities for groundwater observation

Bore-holes:	Observation wells of the all-strainer type
Dug-wells:	Large-diameter wells
Piezometers:	Sets of piezometers of different depths

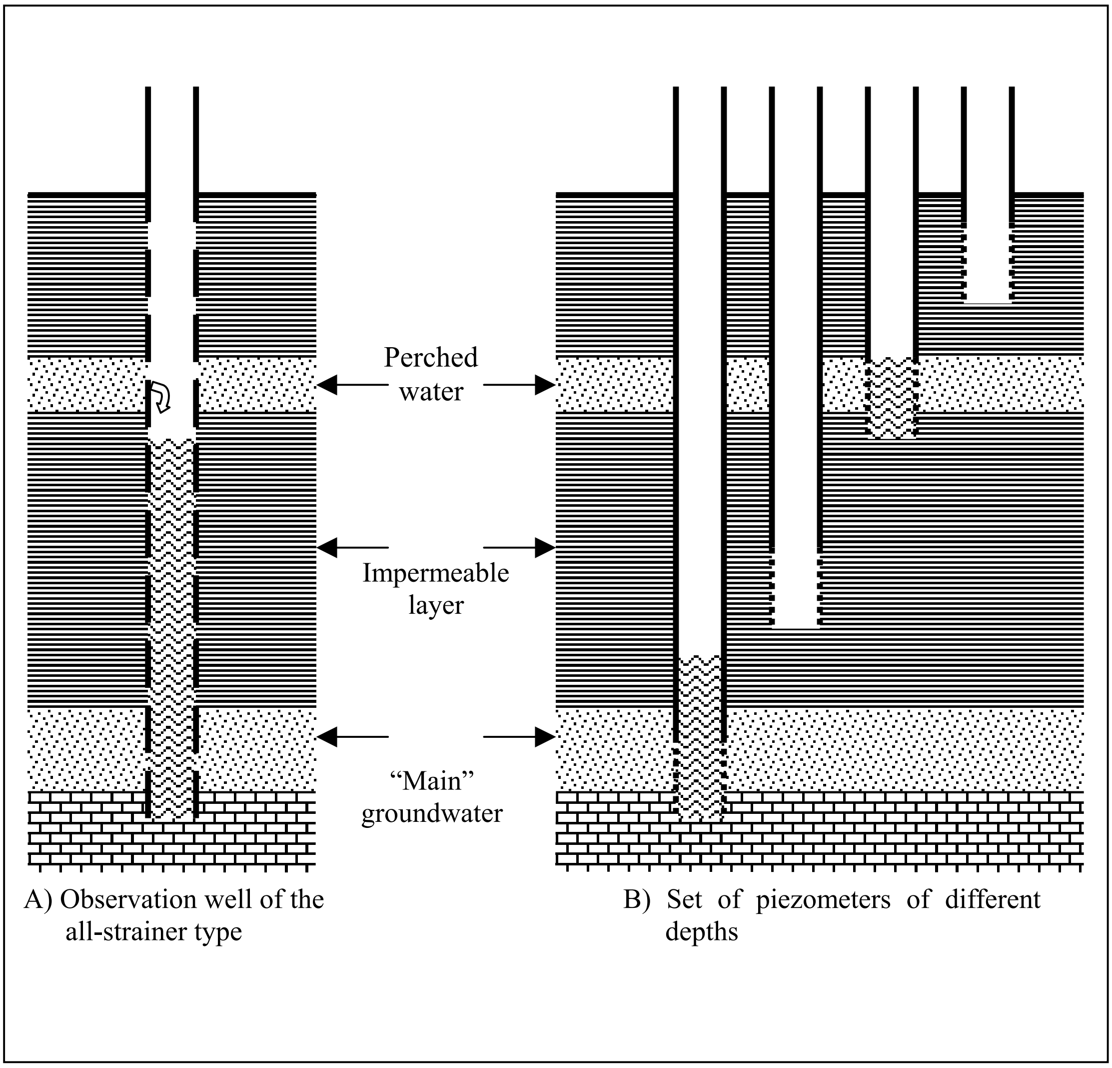


Fig. 6.2: Structure of two types of groundwater observation well

6-2 Results of observation of meteorology and rate of streamflow

The fossil valley where the subsurface dam was built is probably buried along the Kolongo River. A close relationship is thus suggested between the recharge of groundwater stored by the subsurface dam and the rainfall within the Kolongo River basin. In addition, as this area is located in an semi-arid region, much of the water provided by rainfall is probably lost through evapotranspiration.

For a quantitative evaluation of the effectiveness of water storage by the subsurface dam, it is thus necessary to know not only the groundwater level, but also the rainfall within the Kolongo River basin, the amount of evapotranspiration and the rate of streamflow of the Kolongo River. However, almost no such observation has been carried out by the present local authorities. Therefore, observation of these parameters was carried out as a part of this project.

(1) Observation of daily rainfall
The observation of daily rainfall started in 1997 in the Koulikare Quarter, in which the subsurface dam was built, in Nare Village, and in the Kossonkore Quarter of the same village. In 1998, the observation of daily rainfall also started in Ouanobian Village and Noka Village located in the upstream area of the Kolongo River. Table 6.2 shows the results of the observation carried out in Koulikare in Nare Village.

Table 6.2: Rainfall in the Koulikare Quarter in Nare Village from 1997 to 2002

Year of observation	Monthly rainfall (mm)									Annual rainfall (mm)	Cereal harvest
	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	N-F**		
1997*	0.5	19.9	31.9	73.9	123.9	81.0	102.0	35.0	0	468.1	Poor
1998*	0	1.3	55.2	90.8	139.5	157.4	138.9	28.6	0	611.7	Good
1999	0	0.7	13.1	26.8	166.0	189.4	178.2	0	0	574.2	Average
2000	0	8.3	0.9	56.1	112.6	43.5	74.8	20.7	0	316.9	Very poor
2001	0	0.1	20.3	52.0	113.1	169.6	43.5	6.7	0	405.3	Average
2002	0	3.0	75.6	80.2	131.0	166.1	77.8	67.8	0	601.5	Good

* Although the data for 1997 and 1998 were those of the Kossonkore Quarter in Nare Village, they can be considered as almost the same as those of the Koulikare Quarter.
** "N-F" in the last column of "Monthly rainfall" represents the total rainfall from November to February of the following year.

Year 2000 was "a year of extraordinary drought" according to the inhabitants. That year's rainfall was only 316.9 mm as shown in Table 6.2. From just after the dry season of 2000 until just before the rainy season of 2001, the groundwater level in the reservoir area of the subsurface dam dropped markedly. This extraordinary drop in groundwater level was considered due to the exceptional drought of 2000.

The annual rainfall in the Kolongo River basin is shown in Table 6.3. This shows the tendency that the further upstream (to the west-south-west), the greater the annual rainfall.

Table 6.3: Annual rainfall in the Kolongo River basin and its surrounding area

(mm)

	Annual rainfall in the Kolongo River basin (*1)			Outside the River basin (*2)
	Koulikare	Ouanobian	Noka	Kaya
Distance from subsurface dam	At the subsurface dam site	About 15 km upstream	About 35 km upstream	About 50 km upstream
1998	611.7	601.2	616.8	709.6
1999	574.2	718.2	696.1	900.8
2000	316.9	−(*3)	642.1	639.4
2001	405.3	460.4	570.1	504.3
2002	601.5	488.8	791.5	−(*4)
Average	501.9	567.2	663.3	688.5

*1 Observation by this project
*2 Observation by the Meteorological Service of Burkina Faso
*3 This cell is not filled due to numerous missing data.
*4 Data are not available.

(2) Observation of evaporation
In the Koulikare Quarter, in which the subsurface dam was built, in Nare Village, potential evaporation was observed from August 2000 by measuring water loss from an evaporation plate.

Table 6.4 shows the results of the observation between August 2000 and December 2002. These values were corrected considering water loss from the plate due to strong wind.

Annual potential evaporation amounted to 3,700 mm, with the maximum in April and the minimum in August.

Table 6.4: Potential evaporation in the Koulikare Quarter in Nare Village

Average values from August 2000 to December 2002

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monthly evaporation (mm)	306	327	424	476	413	310	281	183	197	259	246	255	3,703
Average daily evaporation (mm)	9.9	11.7	13.7	15.9	13.3	10.3	9.0	5.9	6.6	8.4	8.2	8.3	10.1

(3) Observation of rate of streamflow
To estimate the rate of streamflow of the Kolongo River that probably recharges the groundwater stored by the subsurface dam, the rate of streamflow and the level of the river water were observed at the points where the geometry of the cross-section of the river could be measured easily. The observations were conducted at two points: where the old main road crosses the Kolongo River, and where the current main road crosses the river.

The observation was carried out for 5 years from 1998 to 2002, but reliable results were obtained only in 2000 and 2001. The rate of streamflow where the old main road crosses the river, calculated from the results of the observation, was as follows:
in 2000 (exceptional drought year): about 6,000,000 m^3/year
in 2001: about 11,000,000 m^3/year

6-3 Fluctuation in the groundwater level in the reservoir area

(1) Assessment of the effectiveness of the subsurface dam for water storage
Figure 6.3 shows the water storage state by the subsurface dam at two periods after the construction of the dam, i.e., on 2 October 1998 (at the beginning of the dry season) and from 19 to 24 February 1999 (in the middle of the dry season).

In these two periods, the reserved water level was higher by 4.5 to 6.5 m compared with the groundwater level downstream of the dam. It was also higher by 2.5 to 5 m compared with the groundwater level in the corresponding seasons before the construction of the dam. All these results proved the effectiveness of the subsurface dam for water storage.

(2) Seasonal fluctuation in the reserved water level
However, the reserved water level fell in the dry season, as the comparison of the results of the observation in the two periods in Fig. 6.3 shows. Indeed, some of the reserved water was pumped out, but the amount of such water was tiny compared with the whole reserved water (the amount of pumped out water was 3,000 m^3/year (see Section 7.(1)), whereas the estimated reserved water volume was about 400,000 m^3 at the end of the dry season of 2002 (see Section 6-5)), and could not have caused the fall in the reserved water level.

Such "seasonal fluctuation" in the reserved water level occurred every year. As a proof of this, Fig. 6.4 shows the results of the continuous observation of the groundwater level from June 1998 to February 2003 at the well P-4 (a “well of the all-strainer type”) located about 200 m upstream of the subsurface dam. This figure also shows the groundwater level observed from November 1996 to November 1997 in the well B-2-4 located at the dam site, for comparison with the groundwater level before the construction of the dam.

(3) Interannual fluctuation in the reserved water level
The results of the observation of the reserved water level shown in Fig. 6.4 show the following characteristics of interannual fluctuation in the reserved water level.

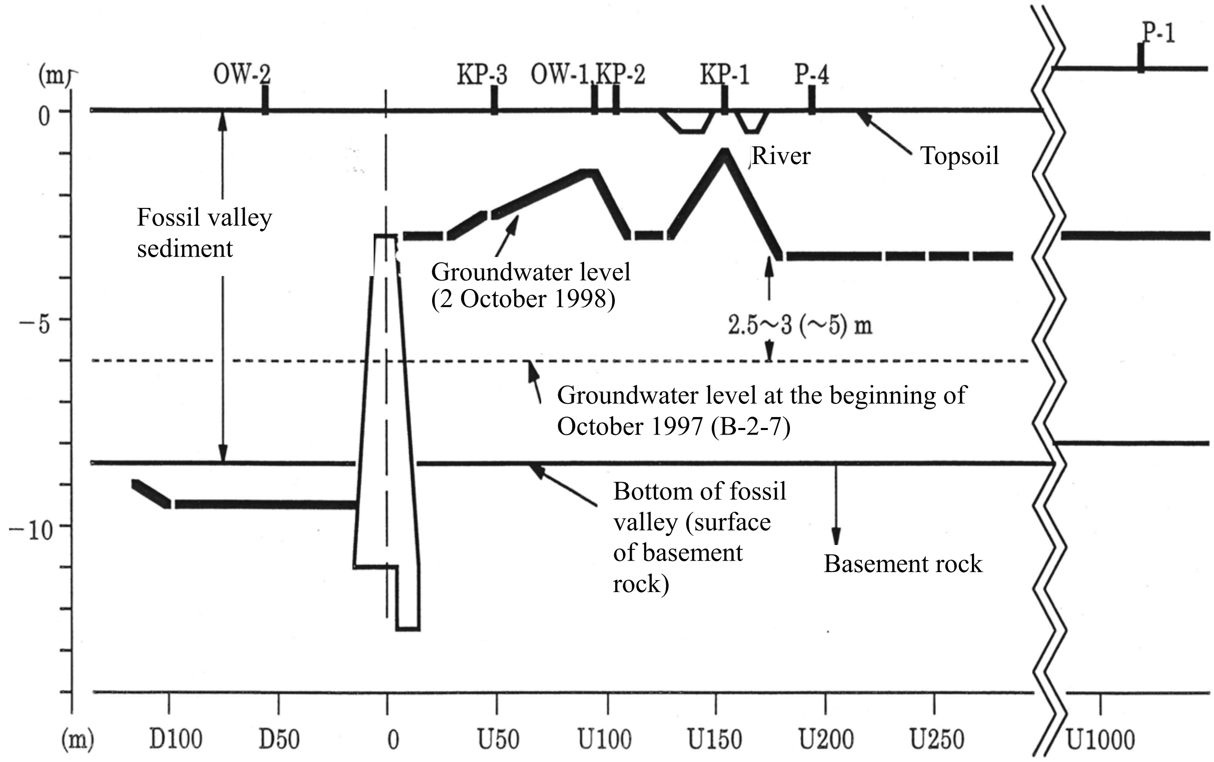
1) Every year, the reserved water level rose in the rainy season and fell by 2.5 to 4.5m by May and June, i.e., between the end of the dry season and the beginning of the rainy season.

2) The lowest level in a year, which was recorded between the end of the dry season and the beginning of the rainy season, rose year by year except in 2001.

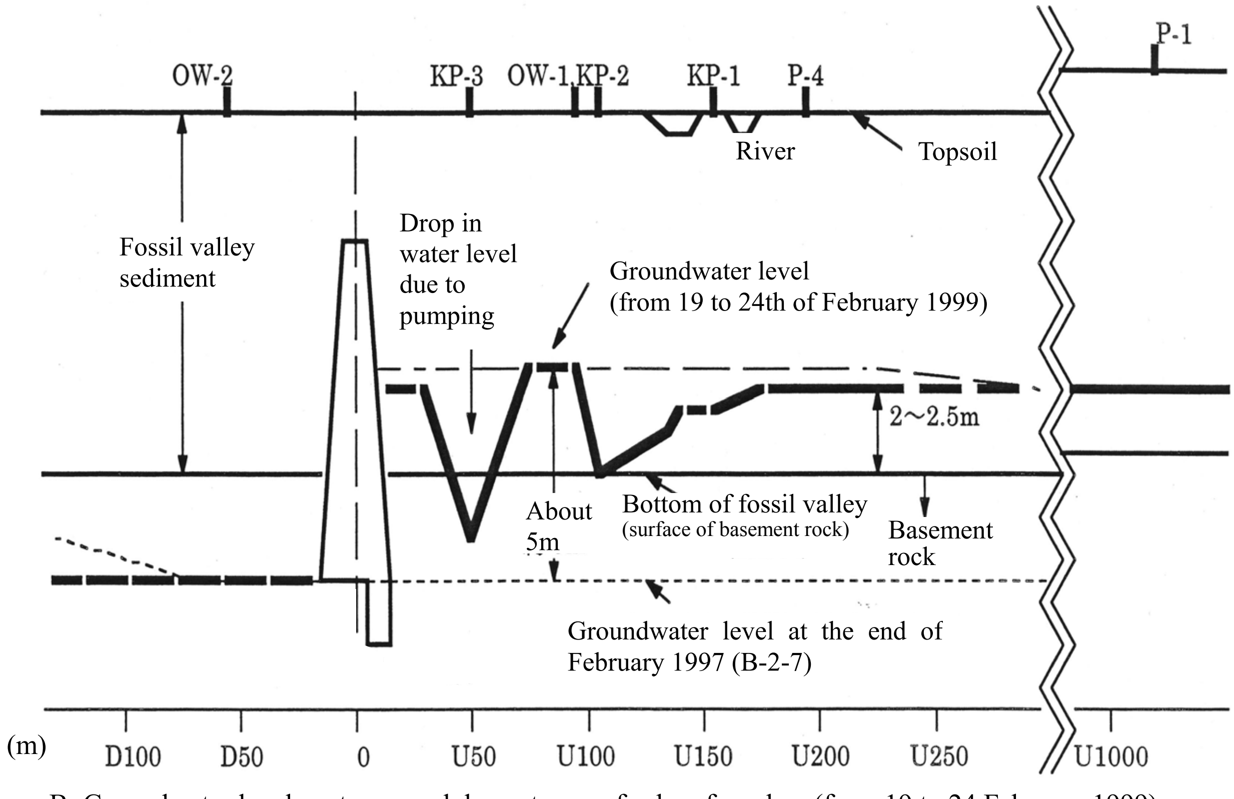
3) The reserved water level during the rainy season of 2000 was very low compared with that of the previous years, and the lowest level between the end of the dry season and the beginning of the rainy season fell in 2001. This can be attributed to the exceptional drought in 2000 around Nare Village. The reserved water level was also low during the rainy season of 2001. It may reflect the fact that the annual rainfall in the upstream area of the Kolongo River basin was lower in 2001 than in 2000 (see Table 6.3). The reserved water level is thus closely related to rainfall within the drainage basin of the river.

Altogether, the reserved water level is rising year by year in spite of the obvious seasonal fluctuation and a fall in the exceptional drought year.

Figure 6.5 shows the interannual fluctuation in the groundwater level observed in the well NP-1 located 5 km upstream of the subsurface dam, which followed a similar pattern of rising with seasonal fluctuation. This interannual rising trend of the groundwater level was also observed in the other wells located upstream of the dam. It was thus concluded that the reserved water level of the subsurface dam is consequently rising with the upstream expansion of the reservoir area. The reservoir area was estimated to reach 5 to 6 km upstream of the subsurface dam in 2002.



A: Groundwater level upstream and downstream of subsurface dam (2 October 1998)



B: Groundwater level upstream and downstream of subsurface dam (from 19 to 24 February 1999)

Fig. 6.3: Change in reserved groundwater storage state

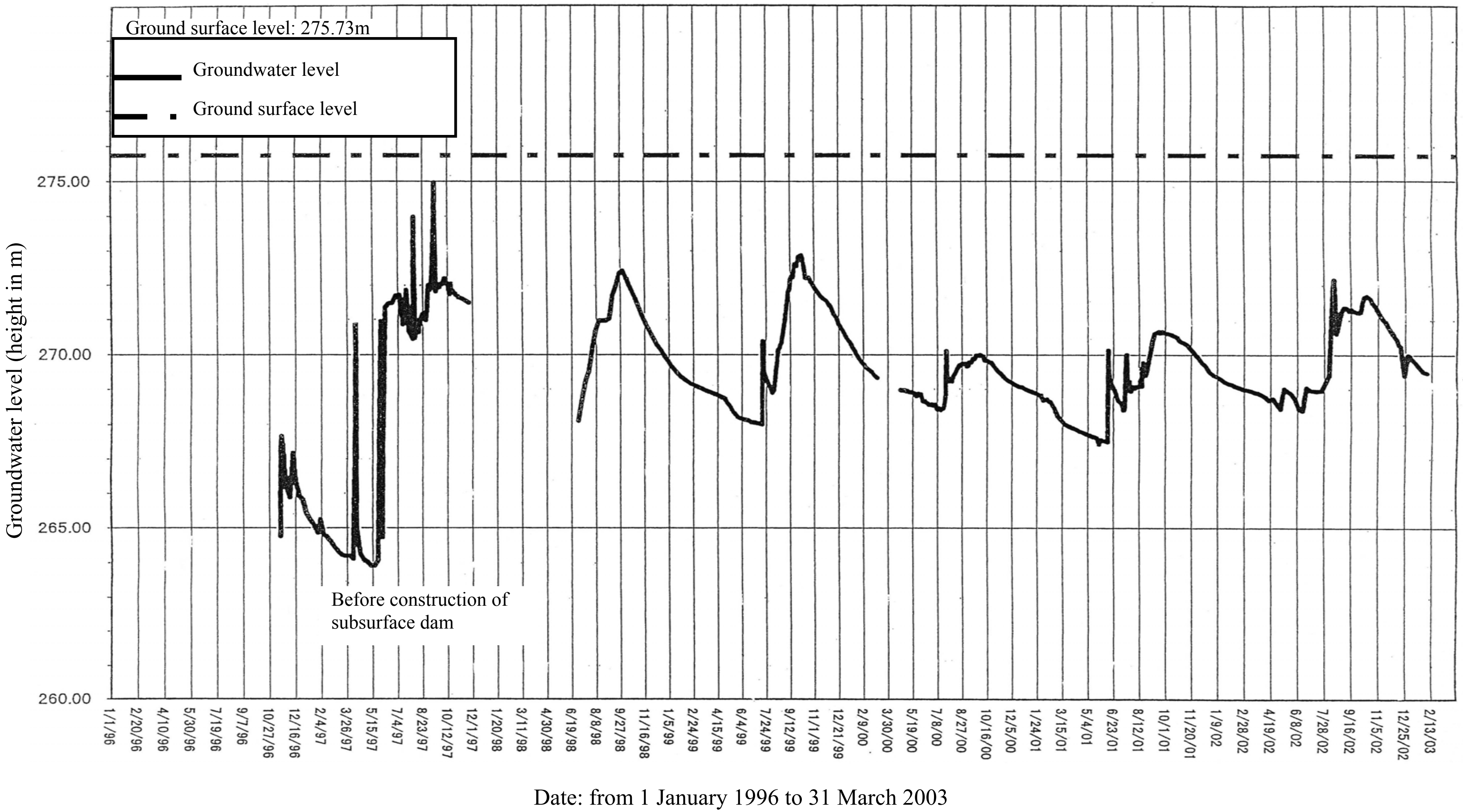
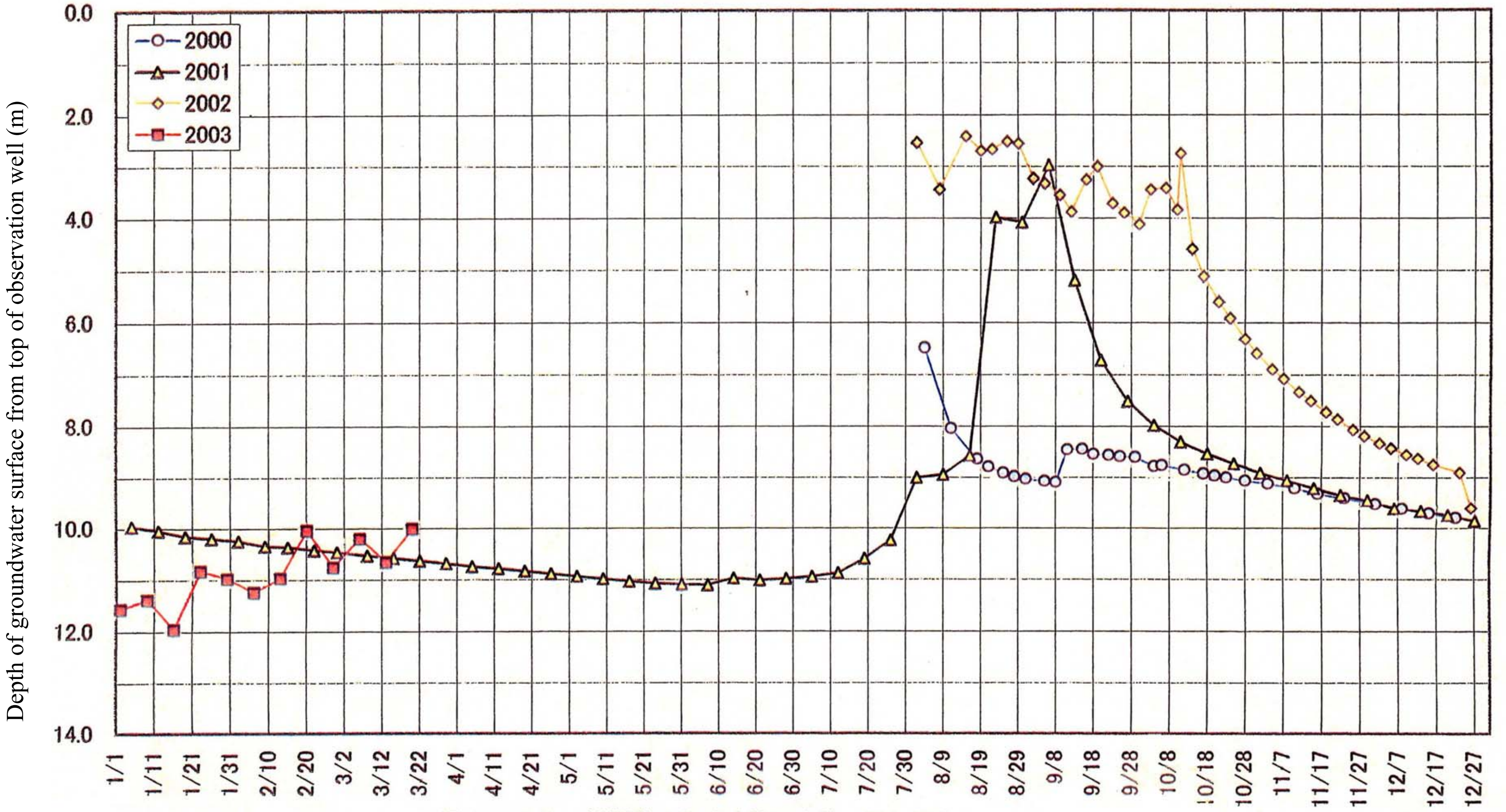


Fig. 6.4: Results of continuous observation of reserved groundwater level by the subsurface dam (at observation well P-4)



The results showed that, in general, the groundwater level increased annually together with the "seasonal fluctuation".

Fig.6.5: Interannual fluctuation in reserved groundwater level (at observation well NP-1)

6-4 Analysis of seasonal fluctuation in the reserved water level

As described in the preceding chapter, although the reserved water level by the subsurface dam rises during the rainy season, it cannot be maintained. It falls considerably once the dry season starts.

"Water leakages" from the reservoir area are a possible cause of this fall in the reserved water level. However, the obvious difference, as shown in Fig. 6.3, of the groundwater level between the upstream and downstream sides of the dam proved that the water shut-off ability of the dam body was sufficient. Therefore, there might be water leakage to the basement rock.

On the other hand, perched water was observed in the "fossil valley sediment" during the excavation. The groundwater level observed in the "well of the all-strainer type" is influenced by perched water, and thus does not precisely represent the "main" groundwater level.

To determine the behavior of the perched water, "sets of piezometers of different depths" with the structure shown in Fig 6.1-B were installed at 4 points (3 of which were in the reservoir area (PA, PB and PC), and 1 of which was about 50 m downstream of the dam (PD)).

The results of the observation confirmed the presence of at least two perched aquifers in the "upper stratum of the fossil valley" that composed the reservoir layer of the subsurface dam. The existence of such two perched aquifers was confirmed in all three observation wells in the reservoir area (PA, PB and PC), and was thus considered to be a common feature of the fossil valley sediment in this area. In neither of the two perched aquifers was there perched water between the end of the dry season and the beginning of the rainy season. During the period in which river water flowed down the Kolongo River and the flood plain was covered with water, the perched water reappeared. With the disappearance of river water, the level of the perched water lowered, and almost disappeared in the middle of the dry season.

As for the "main" groundwater, its level (represented by the lowest water level observed using a "set of piezometers of different depths") started to rise with a certain delay compared with the reappearance of the perched water, and its rising speed was lower than that of the perched water. The highest level of the "main" groundwater in a year was lower than the groundwater level observed using "wells of the all-strainer type" in the same season.

This means that the seasonal fluctuation in the groundwater level observed using "wells of the all-strainer type" was over-estimated compared with that of the "main" groundwater because of the presence of perched water.

Therefore, it is important to take the following into account in assessing the effectiveness of the subsurface dam for water storage from the results of the observation by the "sets of piezometers of different depths" and "wells of the all-strainer type":

1) When there is perched water, the rise in groundwater level observed using a "well of the all-strainer type" during the rainy season does not always represent the rise in the reserved water level by the subsurface dam.

2) During the latter half of the dry season, in which the perched water disappears, the

groundwater level observed using a “well of the all-strainer type” can be regarded as the real reserved water level (the “main” groundwater level).

3) The “main” groundwater level is shown by the lowest level observed using a “set of piezometers of different depths”.

4) When there is perched water, the seasonal fluctuation in groundwater level observed using a “well of the all-strainer type” is probably over-estimated compared with the “main” groundwater level.

However, not only the groundwater level observed using the “wells of the all-strainer type”, but also the lowest level observed using the “sets of piezometers of different depths” showed a fall in the dry season. It is thus certain that there is water leakage to the basement rock. The amount of water leakage probably closely corresponds to the fall in the lowest level observed using “sets of piezometers of different depths”.

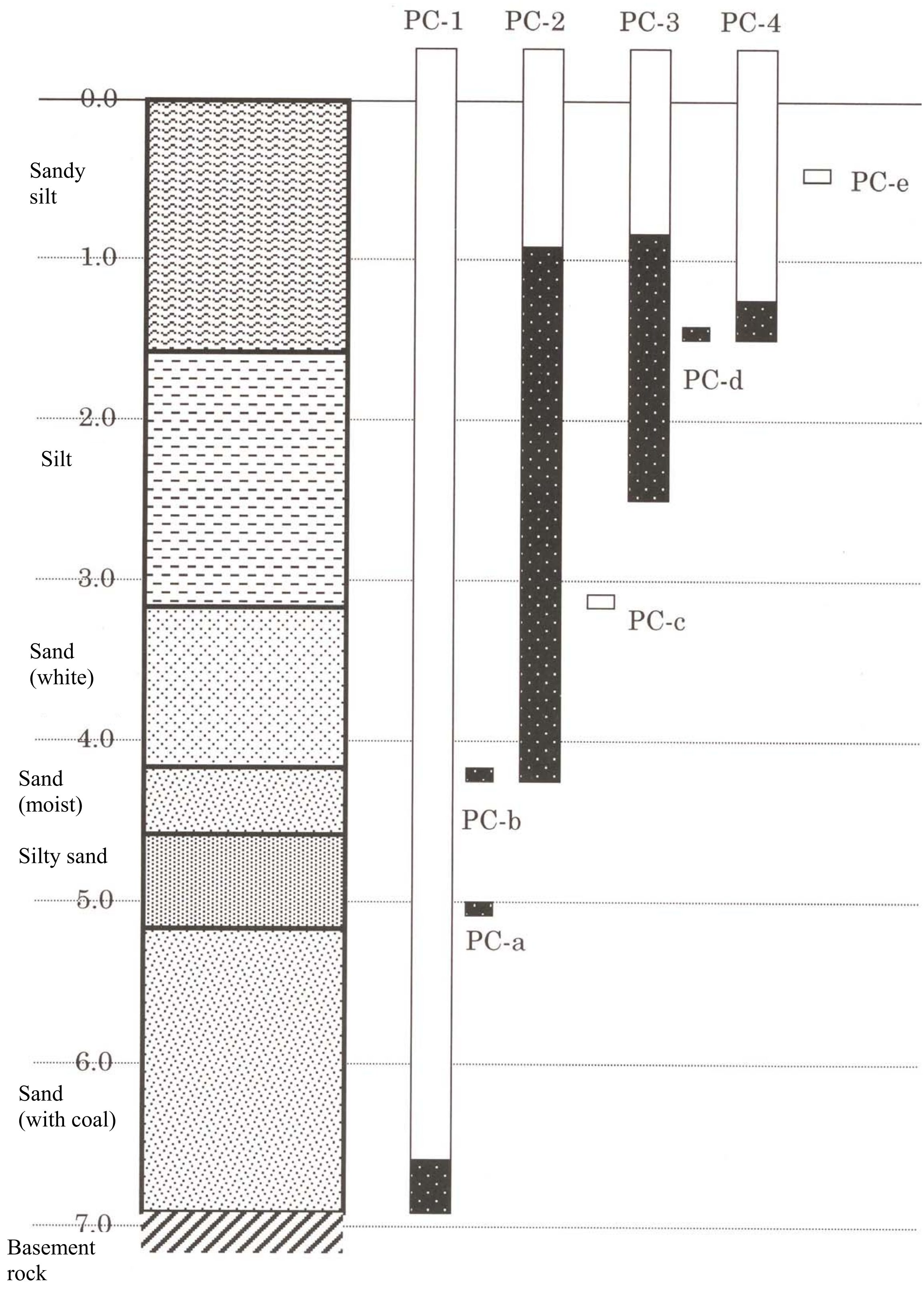


Fig. 6.6: Results of observation using "set of piezometers of different depths " (at observation well PC) (20 July 2000)

6-5 Analysis of water storage state by the subsurface dam

From the results of the study and the observation described above, an analysis of the water storage mechanism by the subsurface dam was carried out according to the flow chart shown in Fig. 6.7.

This report only shows the results of the analysis, omitting the details of the analysis process.

Because of the constraints of the data available, a very simplified method was used for the analysis. Hereafter, further improvement can be examined in the analysis.

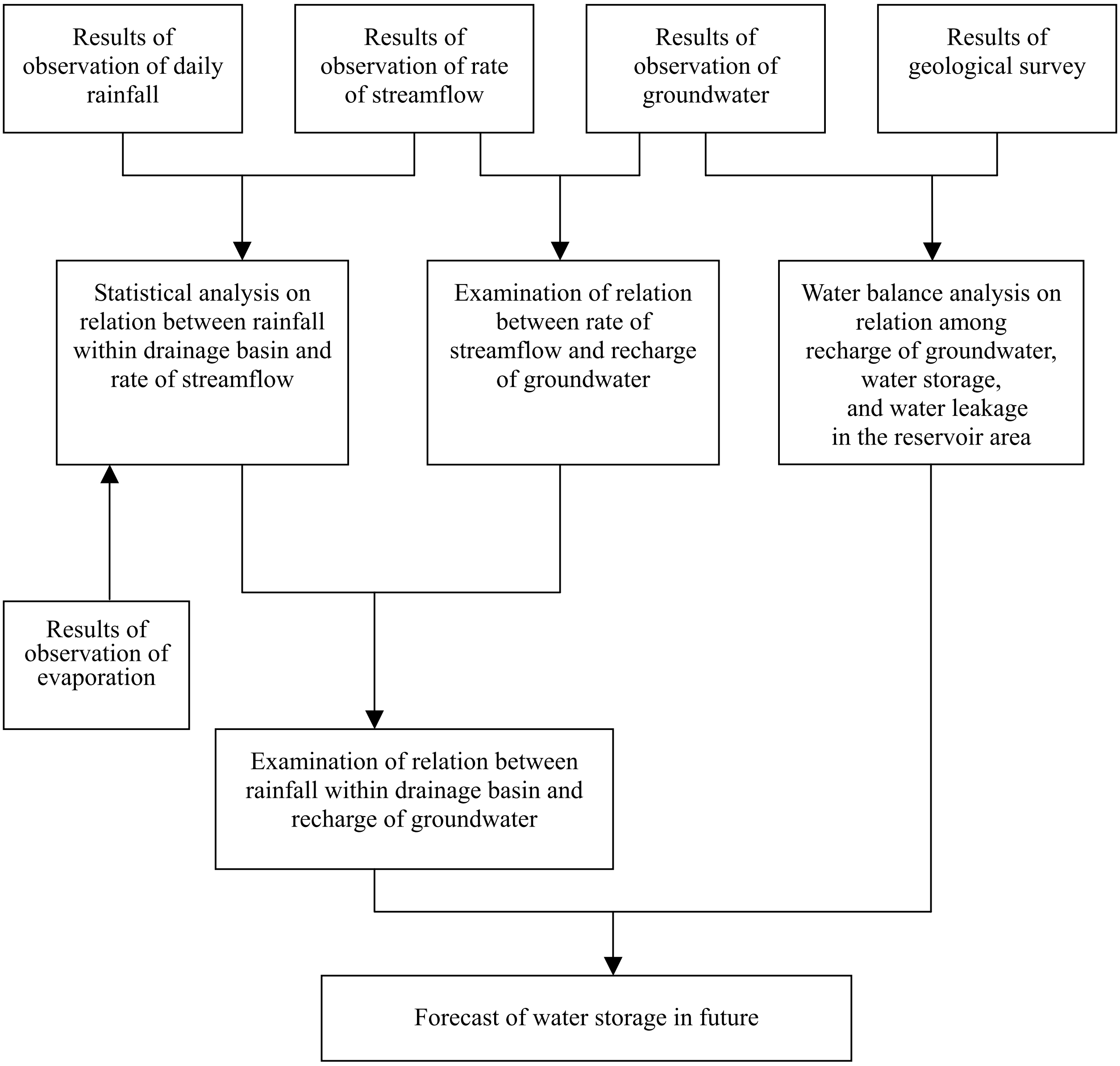


Fig.6.7: Flowchart of analysis of the water-storage mechanism

(1) Relation between the rainfall within the drainage basin and the rate of streamflow
The statistical analysis of the daily rate of streamflow at the crossing point of the Kolongo River with the old main road in Nare Village and of the daily rainfall (*) within the Kolongo River basin provided the relationship shown in Fig. 6.8.
(*The rainfall within the drainage basin was estimated from the rainfall data measured in Nare/Koulikare, Ouanobian, Noka and Kaya.)

(2) Relation between the rate of streamflow and the recharge of groundwater
From the rate of streamflow measured in 2000 and 2001 and the estimated recharge of groundwater, the following relationship was presumed:

Recharge of groundwater = about 10 to 15% of the amount of streamflow (*) from July to October
(*Rate of streamflow at Nare Village)

(3) Relation between the rainfall within the drainage basin and the recharge of groundwater
The relationships given above in (1) and (2) make it possible to estimate the recharge of groundwater from the rainfall measured within the Kolongo River basin.

(4) Dimensions of the reservoir area of subsurface dam
The survey of a longitudinal profile of the reservoir area showed that the slope of the ground surface was 0.65/1000. The digging of the observation wells also revealed that the thickness of the fossil valley sediment (water storage layer of subsurface dam) in the reservoir area was not very different from that at the dam site. Therefore, assuming that the slope of the bottom of the reservoir layer is equal to that of the ground surface, the dimensions of the reservoir are estimated as follows:

- Width of the reservoir area: About 150 m on average (lowest estimate)
- Maximum extent of the reservoir area: 13.4 km upstream of the dam
- Maximum groundwater level: -3 m below ground surface
- Volume of the reservoir layer: About 9,000,000 m^3
- Maximum water storage capacity: 1,800,000 m^3 (assuming that the effective porosity of the reservoir layer is about 20%)

(5) Results of water balance analysis in the reservoir area
From the results of water balance analysis on recharge of groundwater, water storage and water leakage, the water storage state in the reservoir area of the subsurface dam was estimated as shown in Table 6.5.

Table 6.5: Change in water storage state by the subsurface dam

(m^3)

	(1) Recharge of groundwater	(2) Water leakage	Increase in reserved water (1) - (2)	Total amount of reserved water at the end of the dry season
In the rainy season of 1998	1,200,000		(1,200,000)	(1,200,000)
At the end of the dry season of 1999		990,000	210,000	210,000
In the rainy season of 1999	1,200,000		(1,200,000)	(1,410,000)
At the end of the dry season of 2000		990,000	210,000	420,000
In the rainy season of 2000	750,000		(750,000)	(1,170,000)
At the end of the dry season of 2001		990,000	－240,000	180,000
In the rainy season of 2001	1,200,000		(1,200,000)	(1,380,000)
At the end of the dry season of 2002		990,000	210,000	390,000
Total	4,350,000	3,960,000	390,000	390,000

Note: Water storage by the subsurface dam actually started in the rainy se

(6) Forecast of water storage in the future

As Table 6.5 shows, the water leakage from the reservoir area of the subsurface dam is estimated to be about 990,000 m^3 per year. Therefore, when an extraordinary drought occurs as in 2000, reserved water at the end of the dry season of the following year will decrease compared with the previous year.

However, assuming that these droughts are extremely rare and the annual recharge of groundwater on average is about 90% that observed in 2001 (about 1,200,000 m^3), i.e. 1,100,000 m^3, the water storage in the future will change in the following way:

1) With the recharge of groundwater (the increase in reserved water) during the rainy season, the reservoir layer of the subsurface dam will be "full" in the rainy season of 2005. The reserved water will then be about 1,800,000 m^3.

2) However, due to water leakage from the reservoir layer, the reserved water will decrease to about 800,000 m^3 at the end of the dry season of 2006 (until the beginning of the following rainy season).

3) With the recharge of groundwater of 1,100,000 m^3 during the rainy season of 2006 as assumed, the reserved water will reach the maximum capacity of about 1,800,000 m^3, and the excess water of about 100,000 m^3 will overflow the crest of the subsurface dam.

4) Subsequently, the cycle in which the reserved water reached about 1,800,000 m^3 (maximum water storage capacity) in the rainy season and will decrease to about 800,000 m^3 at the end of the dry season of the following year will be repeated.

In this analysis of water storage by the subsurface dam, the fossil valley sediment and its underlying layer, the heavily weathered layer of basement rock, were modeled as the "reservoir layer". Only the reserved water within them was taken into account, and outflowing groundwater from the “reservoir layer” was regarded as "water leakage". However, leakage to the basement rock is recharge of groundwater in the basement rock from another viewpoint. According to the water balance analysis described above, the total water leakage since the construction of the subsurface dam until the end of the dry season of 2002 was about 4,000,000 m^3. This means that the basement rock had been recharged with a large amount of groundwater. Although all this water may not remain in the basement rock in the vicinity of the subsurface dam, a considerable part of it is possibly stored in the basement rock.

Relation between rainfall on drainage basin X (m^3/day) and the daily rate of streamflow Y (m^3/day) in Nare Village

From May to June: **Y＝0.022X＋29,000** Correlation coefficient = 0.615

From July to October: **Y＝0.057X＋38,000** Correlation coefficient = 0.656

To calculate rainfall within the drainage basin X (rainfall multiplied by catchment area), the following corrected values are used, in which E represents the average daily potential evaporation (mm) for the corresponding month.

Catchment areas A1 and A2: {(Rainfall of 3 days ago - 3.4E) + (Rainfall of 2 days ago - 3.4E)}/2
Catchment area A3: {(Rainfall of 2 days ago - 1.0E) + (Rainfall of 1 day ago - 1.0E)}/2
Catchment area A4: {(Rainfall of 2 days ago - 0.6E) + (Rainfall from 1 day ago - 0.6E)}/2
Catchment area A5: Today's rainfall - 0.6E

* If the "daily rainfall - E" < 0, this is considered equal to zero.

The approximate division of the river basin is as follows:

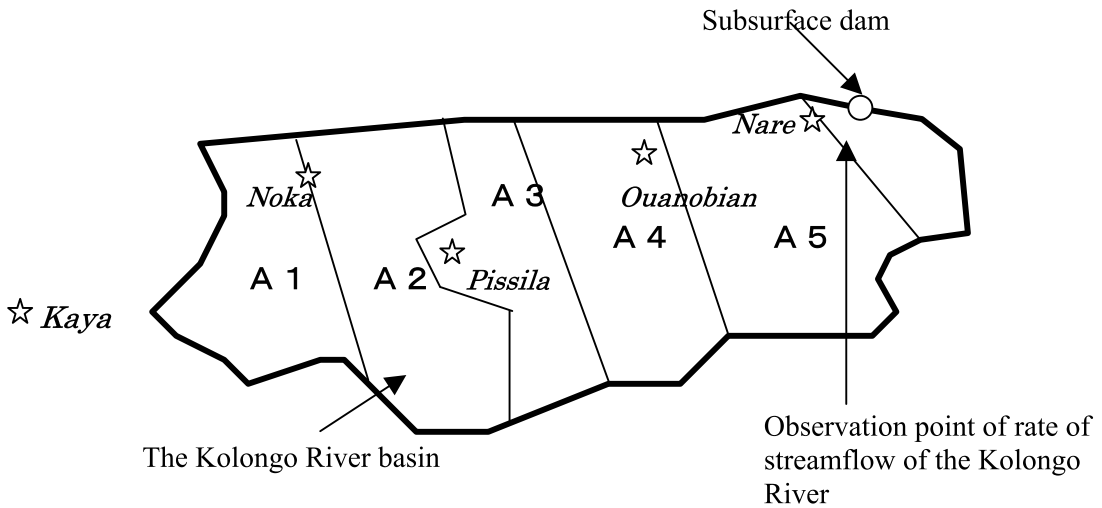


Fig.6.8: Relation between the daily rate of streamflow and rainfall within the drainage basin at observation points in Nare Village on the Kolongo River