環境省
Ministry of the Environment

Model Project to Combat Desertification

In NARE Village, BURKINA FASO

Technical Report of the Subsurface Dam

March 2004

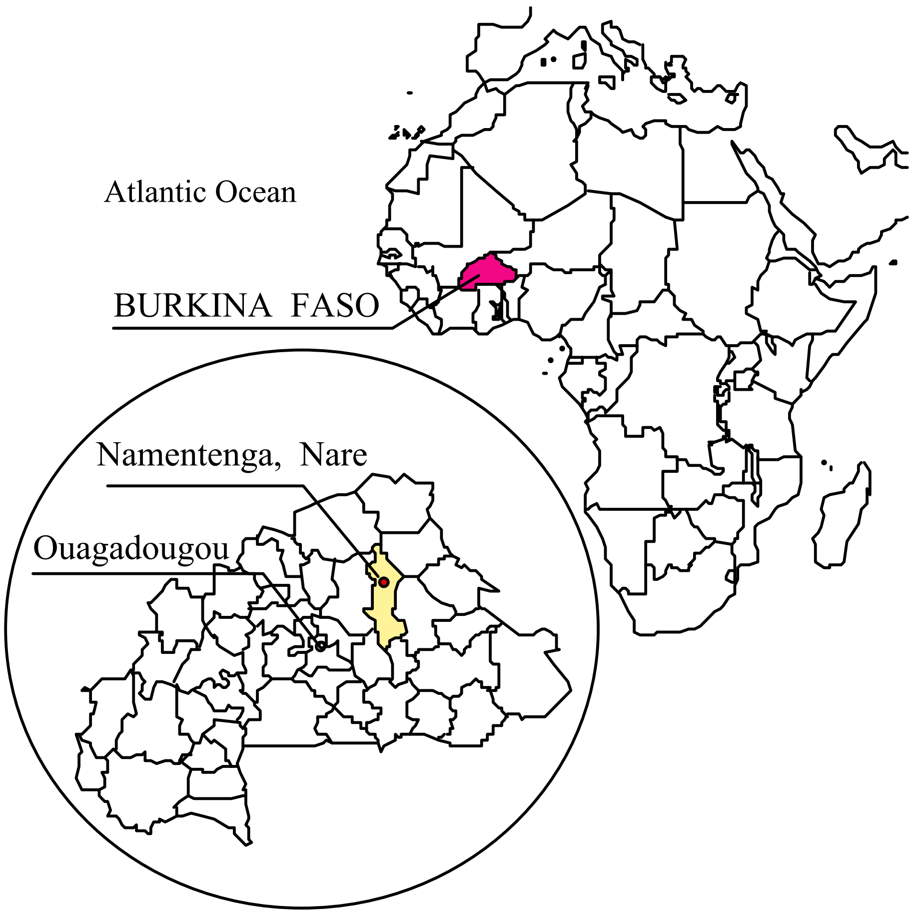
Ministry of the Environment

Overseas Environmental Cooperation Center

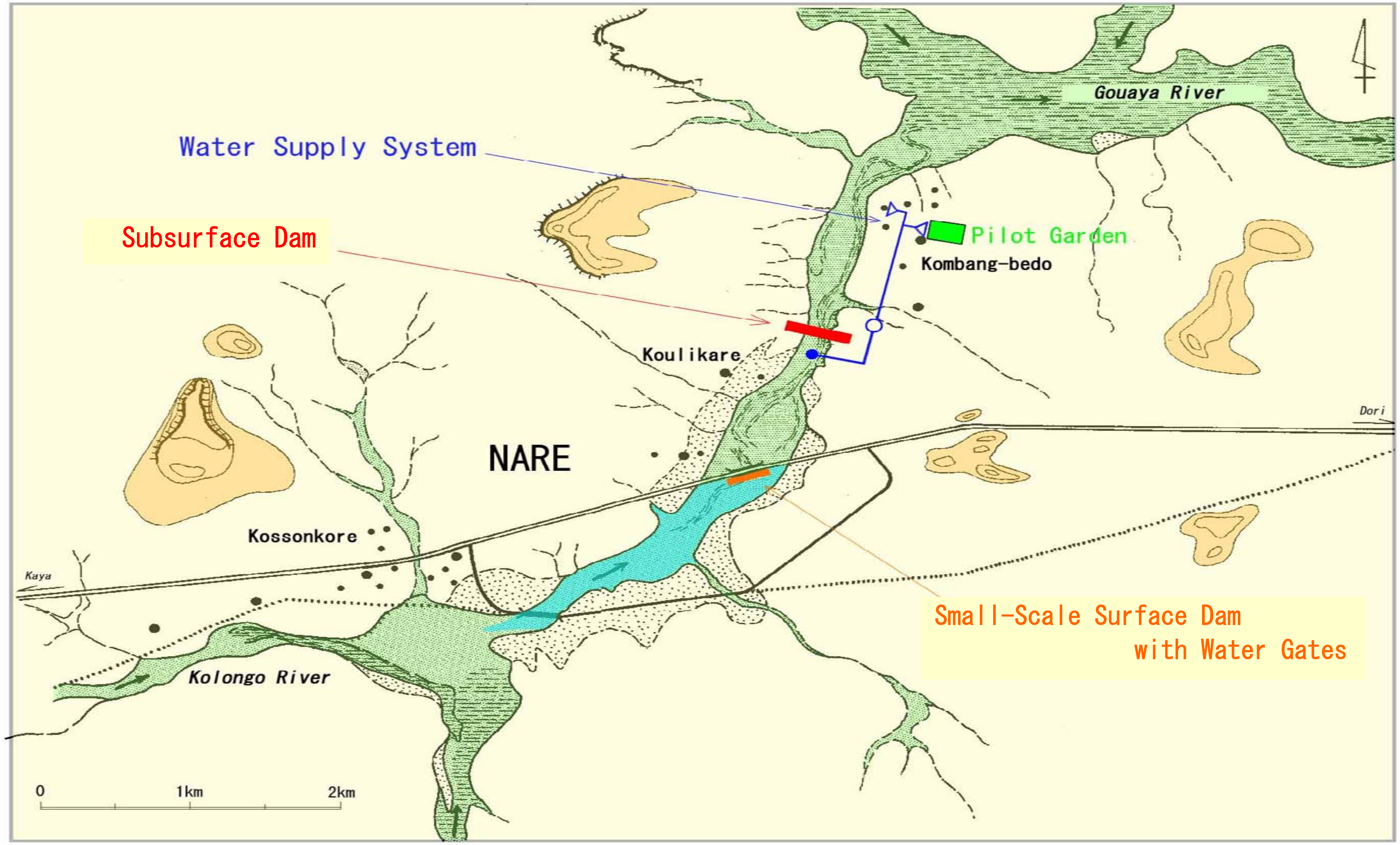
Photo: Construction of the subsurface dam

-Construction of the subsurface dam-

The subsurface dam was constructed by excavating the aquifer layer up to the basement rock, and building a dam body. The pressed part in the photo is the dam body. Parallel to the construction of the dam body, the excavated space of both the upstream and downstream sides of it was backfilled. Finally, the dam body was completely buried under ground.



Project location



Schematic diagram of the location of the facilities for demonstration studies in Nare Village

Introduction

Desertification, a global environmental problem, affects 25% of the world's land and a sixth of the world's population. It particularly affects developing countries, notably in Africa, threatening people's survival.

To find a solution through international collaboration, the United Nations Convention to Combat Desertification was adopted in 1994 and came into force in 1996. Japan accepted it in 1998. The convention specifies that developed countries undertake to provide financial and technical assistance to developing countries affected by desertification. The convention attaches importance, in providing technical assistance, to addressing technologies suitable to the local conditions. Japan is also expected to contribute to combating desertification with its technology. However, as Japan has no areas seriously affected by desertification within its territory, it does not have sufficient information and knowledge on the actual situation of areas under desertification.

The Ministry of the Environment of Japan has been tackling desertification even before the acceptance of the convention. One of its initiatives was the "Model Project to Combat Desertification" carried out from fiscal year 1995 to 2002 in Burkina Faso, a country in the seriously affected West Sahara, with the advice of an advisory committee composed of Japanese experts. This model project developed hardware technology on subsurface dams, which has had operational results in Japan, for the effective use of groundwater in arid and semi-arid areas. It also collected and examined software information and knowledge on the management system of the subsurface dam by local people.

In this model project, after site selection, a subsurface dam was constructed between 1997 and 1998 at Nare Village, Tougouri District, Namentenga Province, in Burkina Faso. After this, studies were undertaken to assess its effectiveness in water storage and its impact on the environment, and to seek appropriate ways to use the reserved water. The model project was finished in March 2003.

This report provides the information and knowledge obtained through the model project not only to Burkina Faso, but also to other countries suffering from desertification, as well to the international community. We sincerely hope that it will serve to combat desertification.

March 2004
Global Environmental Issues Division, Ministry of the Environment, Japan
Overseas Environmental Cooperation Center

Contents

1. General description of the Model Project to Combat Desertification and evaluation of its results

1-1 History and aim of the project

The United Nations Convention to Combat Desertification, adopted in 1994 and put into force in 1996, attaches importance to the use of technologies suitable to local conditions in its implementation.

With particular interest in the technology of the "subsurface dam", which has been developed operationally in Japan, the Ministry of the Environment of Japan conducted the "Model Project to Combat Desertification" to examine, from the viewpoint of both hardware and software, the applicability of this technology under local conditions for the effective exploitation and use of groundwater resources that is invaluable in desertified areas.

In arid and semi-arid areas where desertification continues, surface water and deep groundwater has been focused on in the exploitation of water resources.

In general, surface water is exploited by means of "surface dams". However, a surface dam implies the submergence of a vast land area, and consequently raises problems such as the destruction of environment and the forced migration of the local people. In addition, if it is constructed in flat peneplain in arid or semi-arid areas, the reservoir area of the surface dam, which is large compared with its depth, makes the evaporation rate very rapid. Thus, it cannot work as a "water storage dam" in the dry season when the need for water is the greatest in the year.

In addition, the exploitation of deep groundwater raises a sustainability problem due to its limited volume. There can also be a problem of salinization when the salt concentration of the groundwater is high. In addition, the exploitation of deep groundwater, which is usually conducted point by point, tends to result in the concentration of population and livestock animals, and consequently to accelerate desertification.

To avoid these problems inherent in the exploitation of surface water or deep groundwater, it is necessary to consider the possibility of the exploitation of shallow groundwater, which exists at a shallow depth under ground and flows at a relatively high rate. To exploit shallow groundwater, "subsurface dams" have aroused interest recently. They are the facilities that retain and store groundwater using a dam body. In Japan, this technology is being developed as a new means to exploit water resources in isolated islands that have no large river. In comparison with the surface dam, the subsurface dam has the advantages of having no submerged land area and no risk of collapse because it is constructed under ground. In arid areas, there may be other advantages such as low water loss by evaporation, and less risk of the proliferation of parasites. However, a subsurface dam is accompanied by difficulties in site selection that require an accurate grasp of the hydrogeologic conditions. It is also handicapped by its low effectiveness in water storage, because water is stored in pores in geological strata.

In this project, we chose a subsurface dam for storing shallow groundwater as a means of exploiting water resources in arid and semi-arid areas, and decided to verify its applicability under local conditions in West Africa suffering from chronic drought.

1-2 Execution of the project

This project was carried out from 1995 to March 2003.

(1) Selection of the site country
The United Nations Convention to Combat Desertification notes that serious drought and

desertification has tragic consequences, particularly in Africa.

In this project, Burkina Faso was selected from the Sahel region as a country that meets the following conditions:

1) A country seriously affected by desertification
2) A country with relatively large areas with aquifers of shallow groundwater
3) A country whose political situation is stable

(2) Survey to select the project site, from 1995 to 1996
The interpretation of satellite images and aero-photographs, as well as preliminary exploration, was carried out at 35 sites in the central and the northern part of Burkina Faso, which are areas affected by desertification, to narrow the possible sites for the project. On the basis of the results of electric soundings, test drillings, observations of groundwater level and socio-economic research, Nare Village, Tougouri District, Nametenga Province was finally selected for the project site of the subsurface dam.

(3) Construction of facilities for the demonstration study of a subsurface dam, from 1997 to 1998
Construction of the subsurface dam was carried out during the dry season from November 1997 to June 1998, on the Kolongo River in Nare Village.

Thereafter, during the dry season after October 1998, water-pumping and supply facilities, a small-scale surface dam with water gates, wells for groundwater observation, a pilot farm and other facilities were set up.

(4) Conduct of relevant demonstration studies, from 1999 to 2000
Along with the observation of the water storage state, the following studies were carried out to examine effective groundwater usage and its impact on the environment (in particular, on vegetation):

- Observation of groundwater
- Meteorological observation (mainly of rainfall)
- Observation of rate of streamflow
- Agricultural pilot studies
- Vegetation research

(5) Additional observations, from 2001 to March 2003
In the initial plan, the duration of this project was 6 years (1995 to 2000). However, as the rising speed of groundwater level was lower than expected, it was necessary to continue the observation to verify the effectiveness of the subsurface dam. The project was thus prolonged for 2 years, and the observation of groundwater and rainfall was continued.

(6) Completion of the project
The project was finished in March 2003 with positive results. The Permanent Secretariat of the National Council for the Environment and Sustainable Development (S.P.CONEDD) of Burkina Faso requested that the facilities for the demonstration studies be left to improve and develop the living conditions of the local people. This request was accepted with the hope that these facilities will continue to contribute to combating desertification and to the sustainable development of Nare Village and the whole of Burkina Faso.

1-3 Organizational framework of the project

This model project to combat desertification was carried out under the organizational framework shown in Fig. 1.1.

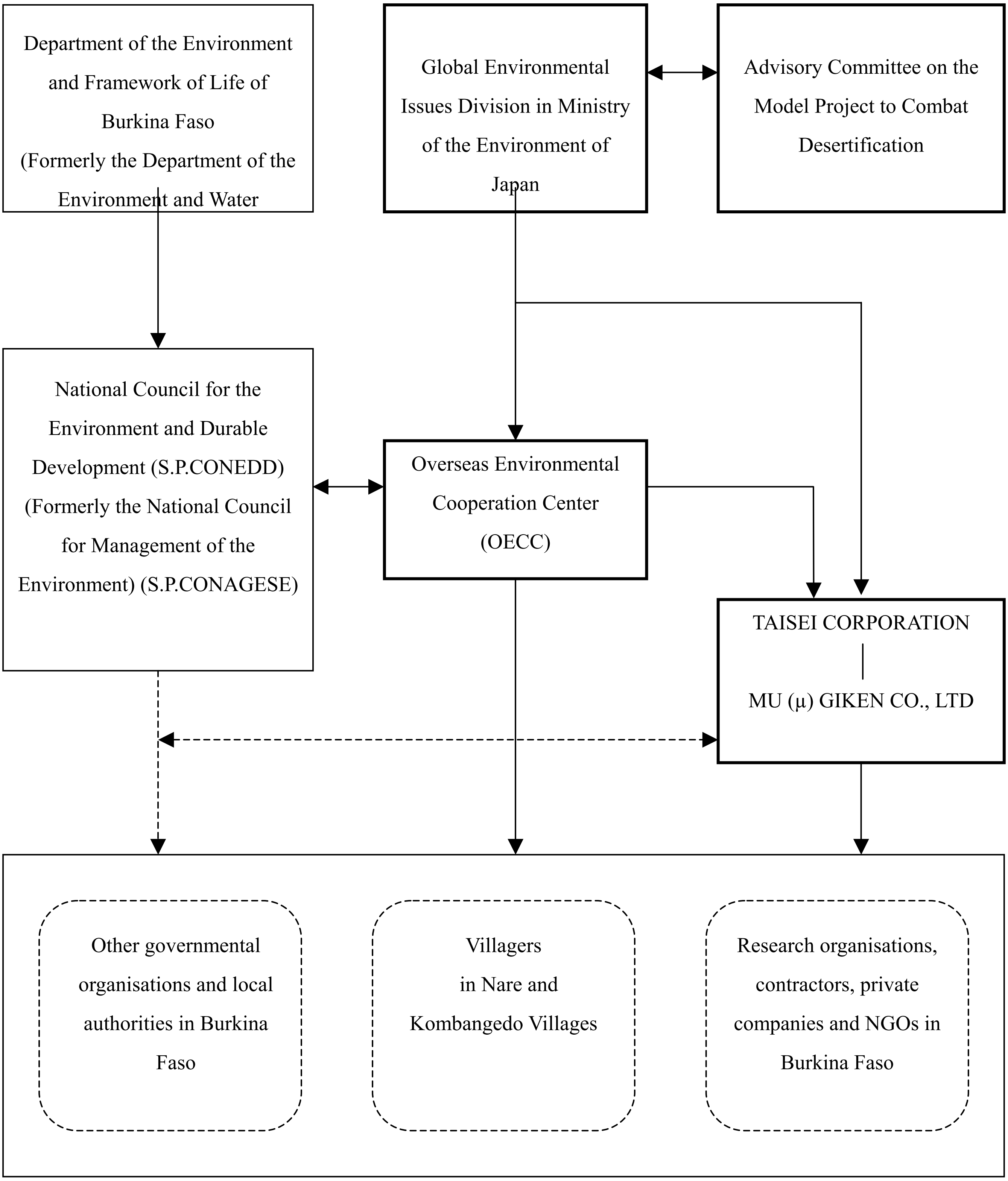


Fig. 1.1: Organizational framework of the project

1-4 Outline of the facilities for the demonstration studies

The facilities for the demonstration studies in this project were as follows:

(1) Subsurface dam
A subsurface dam with the following characteristics was constructed on the Kolongo River at the Koulikare Quarter in Nare Village:

Type: earth dam
Crest length: about 210 m
Depth of dam: 3.0 to 11.4 m (maximum) below the ground surface

(2) Other experimental facilities
- Water-pumping station operated by solar energy: with 3 water-pumping wells (about 20-m depth) located in the reservoir area, with 1.76 kwp of solar power
- Multi-purpose water-supply stations: water-supply stations for domestic, agricultural and livestock uses
- Pilot farm: 0.25-ha area, located in Kombangbedo Village for cultivation tests of cereals and vegetables by methods such as drip irrigation
- Small-scale surface dam with water gates: 33-m width with 23 water gates, maximum water level being 1.2 m, utilizing the bridge piers of a main road located 1.2 km upstream of the subsurface dam site to recharge groundwater

(3) Facilities for groundwater observation
- Facilities for groundwater observation with automatic water level recorders: at 5 points (The water level recorders were removed in 2001 due to decrepitude.)
- Wells for groundwater observation: 3 boreholes and 2 large-diameter wells
- Wells for water pumping and groundwater observation: 2 boreholes and 4 large-diameter wells
- Sets of piezometers (wells for observation of the hydraulic head): 16 pipes located at 4 points

(4) Meteorological stations (mainly of rainfall)
- Meteorological station in the Koulikare Quarter in Nare Village: a station for the observation of rainfall, evaporation, temperature, humidity, etc.
- Rainfall stations in the Kolongo River basin: 3 stations (the Kossonkore Quarter in Nare Village, Ouanobian Village, and Noka Village)

1-5 Evaluation of the results of the project and prospects

(1) Water storage state
The subsurface dam constructed in this project stores water in the reservoir layer consisting of "fossil valley sediment" and heavily weathered basement rock. According to the calculation using a simplified reservoir model, the extent of the reservoir area, the groundwater level and the volume of the reservoir at its maximum storage capacity are as follows:

- Width of the reservoir area: about 150 m (lowest estimate)
- Length of the reservoir area (upstream distance to which the reserved water extends): 13.4 km
- Maximum groundwater level: -3.0 m (depth below the ground surface)
- Water storage capacity: about 1,800,000 m^3 (with the effective porosity of the reservoir layer estimated to be 20%)

Up to the end of 2002, the groundwater level (depth below the ground surface) varied from -7.0 m at the end of the dry season to -4.2 m at the end of the rainy season, and had not yet reached the maximum level. The reservoir area probably extended 5 or 6 km upstream of the dam, and the volume of reserved water was thus estimated to be about 400,000 m^3 at the end of 2002.

According to the results of an analysis of water balance in the reservoir area, a recharge of groundwater of about 1,100,000 m^3/year is estimated in the rainy season if the rainfall is that of an average year. On the other hand, with leakage of about 1,000,000 m^3/year, the effective increase in the reserved water is estimated to be 100,000 m^3/year.

If the reserved water increases at this rate, it will reach the maximum storage capacity of about 1,800,000 m^3 during the rainy season of 2005. At the end of the dry season of the following year, the volume will fall to 800,000 m^3 because of leakage. Subsequently, the reservoir will follow this cycle with a maximum of 1,800,000 m^3 in the rainy season and a minimum of 800,000 m^3 in the dry season of the following year.

The water leakage is due to infiltration into the basement rock, not due to the insufficient water shut-off ability of the dam body. This means that the infiltrated water is stored in the basement rock.

It should be noted that reserved water using the subsurface dam, via the three "water-pumping wells operated by solar energy", supplies local people with 7.4 m^3 water per day, i.e., roughly 2,700 m^3 water per year.

As noted above, water is being stored gradually although its speed is lower than expected due to unexpected water leakage. It is thus proved that the subsurface dam can supply water even in the dry season. To avoid the problem of water leakage (infiltration into the basement rock), it was necessary to carry out a more detailed hydrogeological survey at the stage of site selection.

(2) Costs

The direct costs of the construction of the subsurface dam and installation of the water-pumping and supply stations were as follows:

- Construction of subsurface dam: 108,595 thousand yen
- Installation of water-pumping and supply stations: 24,900 thousand yen (a part of which is estimated)

The construction of the subsurface dam was wholly supervised by Japanese engineers, but their personnel costs are not included in the above.

(3) Management and maintenance system

The management and maintenance of water resources requires "ownership" by local people and local authorities. As for this subsurface dam, a system to collect a water tax has already set up at the site village to cover the cost of minor repairs to the facilities. However, to maintain the continuous operation of the facilities, it is necessary to set up a longer-term management and maintenance system.

(4) Impact on the environment

No significant impact on the environment, in particular on the vegetation, was noted until the end of 2002, 5 years after the construction of the subsurface dam. It was due, among other things, to the dam site being located near the confluence point of the Kolongo River into a larger river.

(5) Applicability to other areas

This model project is probably a rare study on the exploitation of water resources using a subsurface dam in arid and semi-arid areas. In areas where there are fossil valleys, subsurface dams, using the information and the knowledge obtained from this project, is worth consideration to exploit shallow groundwater to combat desertification.

2. What is a subsurface dam?

2-1 Concept and principle of a subsurface dam

A subsurface dam is a system to store groundwater by a “cut-off wall” (dam body) set up across a groundwater channel.

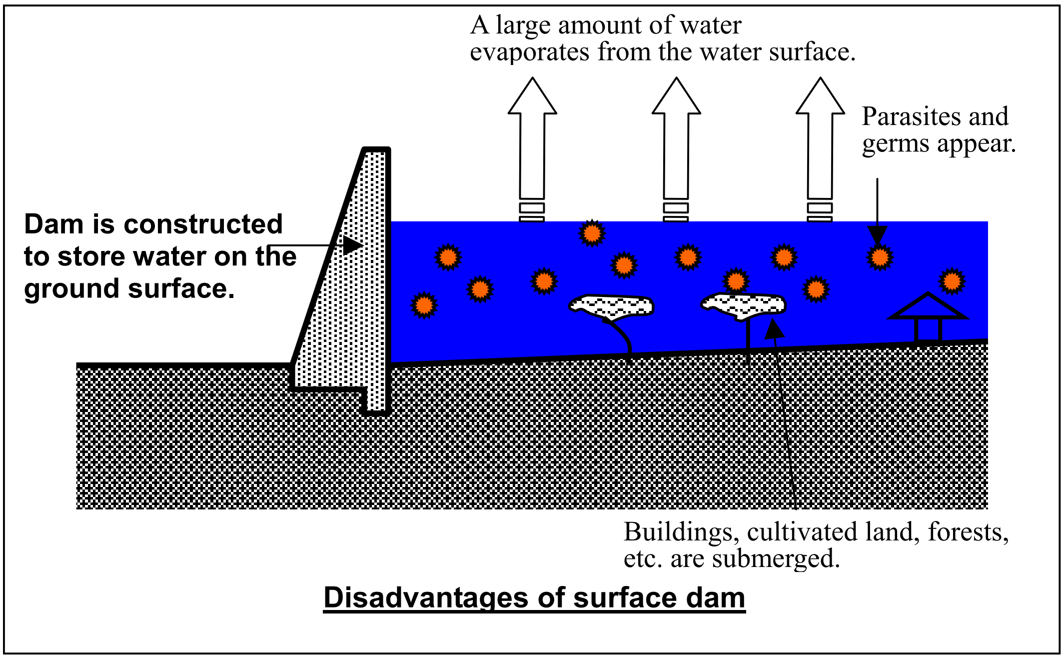
It is similar to a "surface dam" in its function of water storage by a dam body, but is different in the following areas:

(1) A system to store groundwater
In contrast with a surface dam that stores surface water (river water), a subsurface dam stores groundwater. In general, it stores shallow ground water because a subsurface dam to store deep groundwater needs huge-scale construction.

(2) Storage in geological strata
Groundwater is stored in geological strata. In other words, a subsurface dam is a system that artificially recharges natural aquifers.

(3) A dam constructed under ground
To store groundwater, a dam is constructed under ground. However, in the case of a dam to store very shallow groundwater like underflow in the current river sediment, part of the dam is sometimes exposed above the ground surface.

(4) Necessity for water-pumping facilities
The reserved groundwater level is lower than the ground surface because the dam is constructed under ground. Therefore, for using the reserved water, water-pumping facilities are essential.



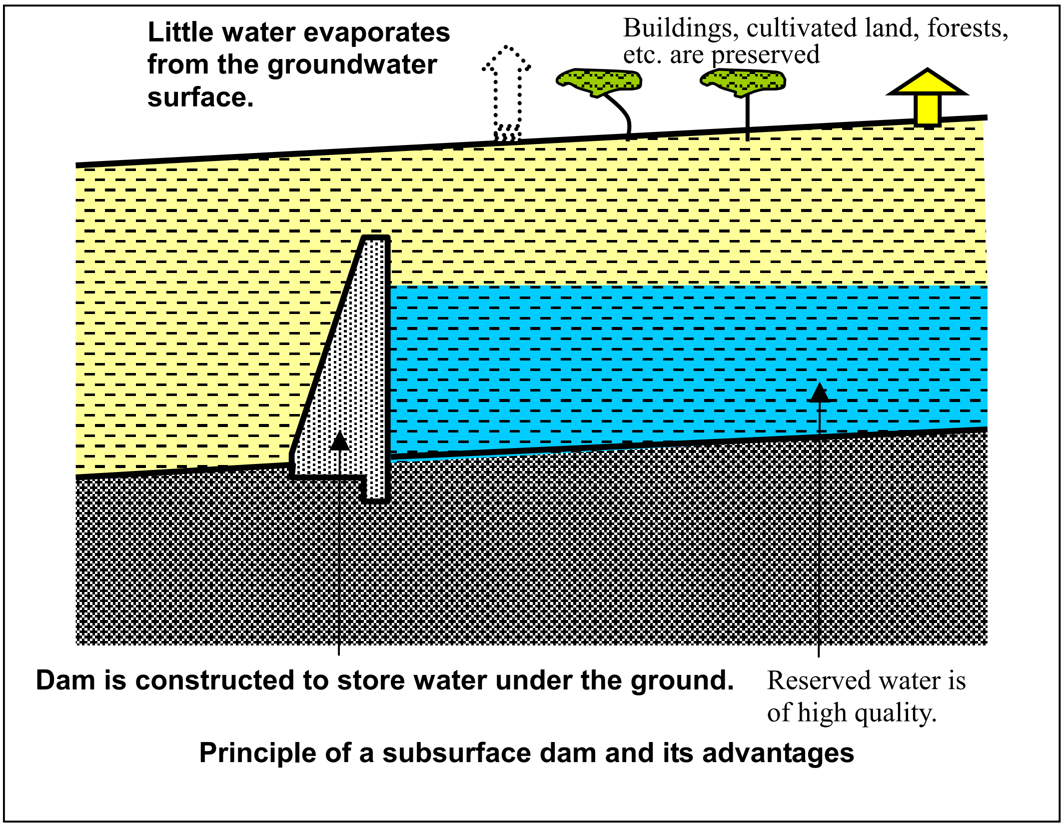


Fig. 2.1: Principle of a subsurface dam

2-2 Advantages of a subsurface dam

Compared with a surface dam, a subsurface dam has the following advantages:

(1) A water storage system without land submergence
A subsurface dam does not submerge land area in contrast with a surface dam because it stores water under ground. Therefore, it does not seriously damage the environment, nor does it cause social problems such as the forced migration of the local people.

(2) Prevention of evaporation of reserved water
A subsurface dam does not lose reserved water by evaporation because water is stored under ground and there is very little evaporation, in contrast with a surface dam that often loses a significant amount of reserved water due to evaporation in the dry season in arid or semi-arid areas.

(3) Clean, safe water
Reserved water using a subsurface dam is of fairly good quality because it is stored under ground, and it can be used like ordinary well water, in contrast with reserved water using a surface dam that tends to proliferate parasites, anopheles that transmit malaria, and germs, and requires purification for domestic use.

(4) A stable, secure dam
In general, a subsurface dam is more stable than a surface dam from the viewpoint of dynamics because it is buried under ground, and thus does not need maintenance. Even if it breaks, there is no damage to the downstream area because the breakage occurs under ground.

(5) Utilization of renewable resources
Shallow groundwater consumed via a subsurface dam system is renewable because it is recharged with rainfall. Therefore, a subsurface dam does not exhaust water resources.

2-3 Disadvantages of a subsurface dam

However, it is necessary to note that a subsurface dam also has the following disadvantages:

(1) Difficulties in site selection
Contrary to a surface dam whose site conditions can be examined by visual inspection, surveys for site selection and calculating the water storage capacity of a subsurface dam rely on estimates of underground geological structures.

(2) Low effectiveness of water storage
In case of a subsurface dam, water is stored in the pores of geological strata. Therefore, the volume of reserved water is determined by the volume of those pores (effective porosity), and reaches only 10 to 30% of the volume of the reservoir layer.

(3) Interception of downstream groundwater flow
A subsurface dam may prevent downstream groundwater flow, and exhausts groundwater in the downstream area. However, groundwater in the downstream area is not always recharged only with groundwater from the dam site area. It is also possible to design a dam with a structure that allows some of the reserved water to drain. Therefore, this problem can be avoided by appropriate site selection that considers the mechanism of groundwater flow, or

by adopting an appropriate dam structure.

In this project, this problem was solved by selecting the dam site at a point near the confluence of the Kolongo River into a larger river.

(4) Salinization in reservoir area
The subsurface dam is likely to cause accumulation of salt on the ground surface in the reservoir area due to the rise of reserved groundwater to the surface by evaporation. However, this phenomenon occurs only when the highest groundwater level is close to the ground surface. It is thus possible to avoid this problem by setting the highest level of reserved groundwater at a sufficient depth below the ground surface.

In this project, the highest level of reserved groundwater (the depth of the crest of the dam) was thus set at 3 m below the ground surface.

2-4 Requirements for a subsurface dam site

The physical conditions (hydrogeological conditions) required for the site are as follows:

(1) Presence of shallow groundwater with high fluidity
There must be groundwater at the dam site. This groundwater must have high fluidity as well, because reserved water using a “cut-off wall” set up across stagnant water cannot increase.

In addition, it is desirable that this groundwater exists at a shallow depth because, if the groundwater aquifer exists at a deeper depth, determining the hydrogeological characteristics of the dam site would be more difficult, and the cost and technical difficulties of the construction of the subsurface dam would be much greater.

(2) Presence of a porous layer (aquifer) for water storage
The higher the volume of pores (effective porosity) of the geological strata that form the reservoir layer, the more effective the water storage. This is because water is stored in the geological strata. High effective porosity is necessary also for high water fluidity.

(3) Presence of the surrounding basement rock with low permeability
The sides and the bed of the reservoir must consist of basement rock with low permeability. If there are big water bypaths, the dam cannot store water effectively.

(4) Presence of a gorge of basement rock with low permeability
To construct a subsurface dam effectively, it is desirable to set up the dam at a bottleneck point, where basement rock with low permeability make a gorge with a vast aquifer upstream, as in the case of a surface dam.

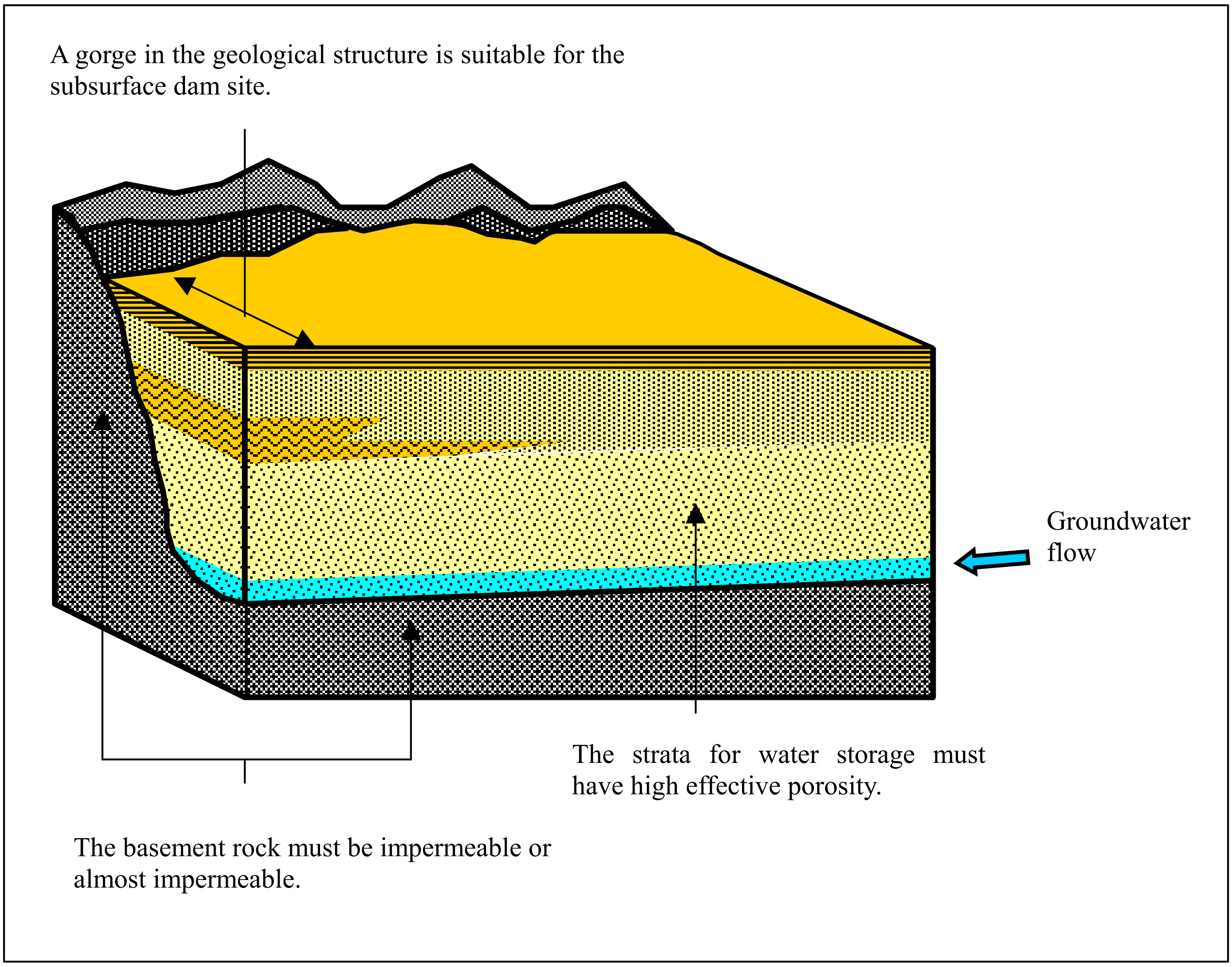
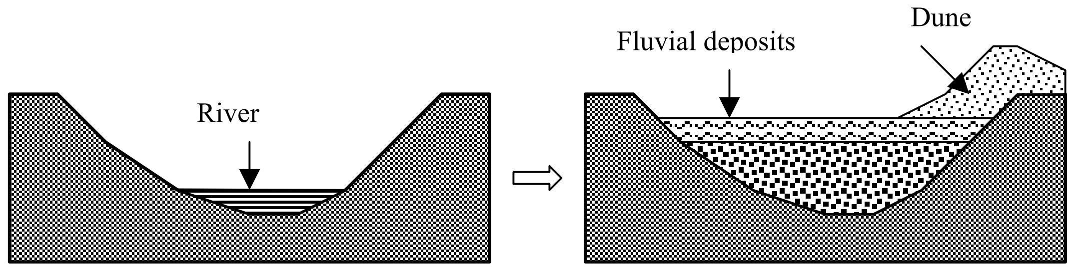


Fig. 2.2: Requirements for a subsurface dam site

2-5 "Fossil valley", a suitable site for a subsurface dam

(1) What is a "fossil valley"?

A "fossil valley" is a geomorphological and geological structure that meets the requirements described above. It is formed by erosion by an old river and subsequently covered by new sediment. It is also known as a "buried valley".



Formation of a valley by an old river

Buried valley (fossil valley)

Fig. 2.3: Schematic diagram of a "fossil valley"

(2) Characteristics of a "fossil valley"

A fossil valley is generally regarded as having the following characteristics suitable for a subsurface dam.

1) As a “fossil valley” is an old buried river (valley), it is likely to preserve the drainage system of the old river as shallow groundwater flow in stable regions that have not experienced crustal movement in recent geologic ages. In addition, it probably does not have irregular "water bypaths".

2) In the case of a “fossil valley” formed by the erosion of basement rock, its sides and bed are impermeable, and there is less risk of water leakage from the reservoir layer.

3) The "fossil valley sediment" that buries the “fossil valley” is composed of deposits from recent geologic ages such as fluvial deposits or sand originating from dunes. This porous, unconsolidated sediment is favorable for the reservoir layer of a subsurface dam.

3. Survey to select the subsurface dam site

This chapter describes the survey methods of selecting a subsurface dam site and the results.

3-1 Outline of the survey methods

Generally, a subsurface dam site is selected according to the following procedure:

1) Interpretation of satellite images and aero-photographs
2) Geological and topographical survey by preliminary exploration
3) Estimate of the geological structure by geophysical surveys such as electric soundings
4) Verification of the geological structure by test drillings and permeability tests
5) Estimate of the flow mechanism of groundwater by observation of groundwater level

Hydrological and meteorological data, such as rainfall and rate of streamflow, are also collected to determine the need and feasibility of a subsurface dam.

On the other hand, management and maintenance of a subsurface dam requires the active participation of the local community. Therefore, it is necessary to undertake a socio-economic study to understand the potential for the participation of the local people. Once the site has been decided, it is also important to encourage their participation from the planning stage.

3-2 Selection of the project area

(1) Selection of the country for the project
The United Nations Convention to Combat Desertification notes in its preamble that serious drought and desertification has tragic consequences particularly in Africa. Originally, the UN started to deal with the desertification issue, with the serious drought in the Sudan-Sahel region at the end of 1960s to the beginning of 1970s as a trigger. For these reasons, it was decided that this model project be carried out in the Sahel region. Burkina Faso (in particular, the central and the northern part of this country) was finally selected as the site country because it met the following conditions:

1) A country seriously affected by desertification
2) A country with relatively large areas with aquifers of shallow groundwater
3) A country whose political situation is stable

The climate in the northern part of Burkina Faso is characterized by two seasons:
- Dry season (8 months from October to May)
- Rainy season (4 months from June to September)

There are two temperature peaks in a year in this country; the hottest is March to May with a maximum temperature of about 40 degrees centigrade and a minimum temperature of 25 to 28 degrees, and the second hottest is October to November with a maximum temperature of 36 to 39 degrees and a minimum temperature of 22 to 23 degrees. In addition, there are two coolest seasons; December to January with a maximum temperature of 30 to 34 degrees and a minimum temperature of 14 to 16 degrees, and July to September with a maximum temperature of 30 to 34 degrees and a minimum temperature of 21 to 24 degrees.

Going north in this country, rainfall decreases. Ouagadougou, the capital of Burkina Faso located in the central part of the country, has an annual precipitation of 733 mm (annual average between 1990 and 1994), while Dori, a city located in the north-eastern part of the country, has annual precipitation of 474 mm. Most of the rainfall is concentrated in the rainy season.

A total of 80% of the land of the country is on the old rock of the Precambrian.

The main industries of the country are agriculture and livestock farming. A total of 11% of the country is used as farmland, on more than 80% of which millet, sorghum, maize and rice are cultivated. However, the production of these cereals is not stable due to their sensitivity to land conditions and climatic conditions.

(2) Requirements for the selection of the model project site

In particular, the following are taken into account in site selection from the viewpoint of executing the model project:

1) The construction of a subsurface dam of appropriate scale as a model project is feasible at the site.
2) There is a relatively large village near the site to facilitate the participation of local people in the model project.
3) Access to the site from the capital, Ouagadougou, is easy.
4) There are no other projects near the site, to assess the result of the model project properly.

(3) Procedure for the site selection in this project

In this project, the subsurface dam site was selected according to the procedure shown in Fig. 3.1. Equipment and machinery available in Burkina Faso were used as much as possible for the project, avoiding the use of special equipment or machinery.

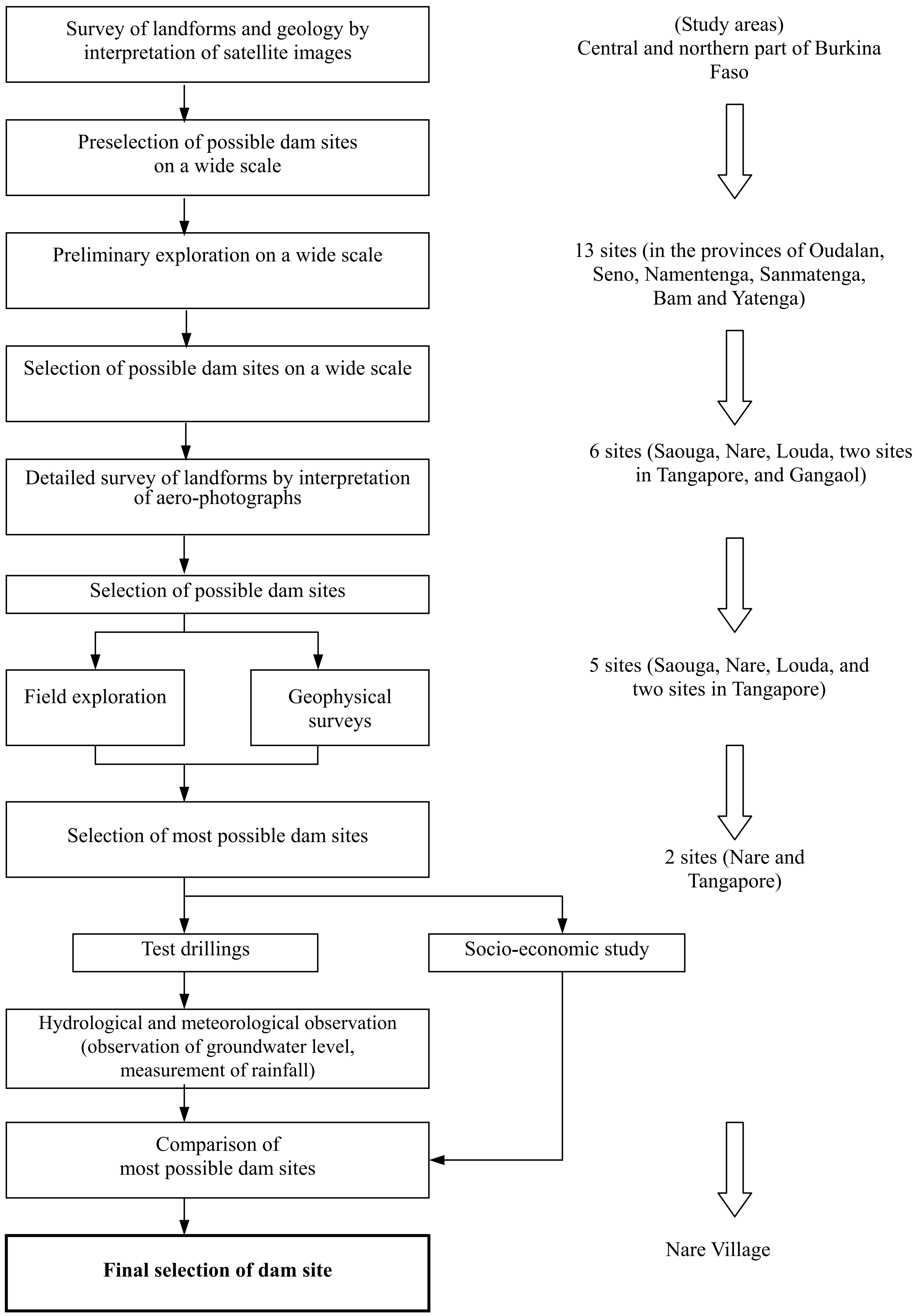


Fig.3.1: Flowchart of the site selection for the subsurface dam

3-3 Distribution of fossil valleys in West Africa

From 1989 to 1999, before launching this project, a feasibility study of the construction of subsurface dams was carried out in Niger and Mali in the Sahel region by a study group (the Sahel Greenbelt Study Group) sent by several Japanese companies. The results showed that the Niger River basin contain a good number of fossil valleys with a hydrogeological structure suitable for subsurface dams. In this study, the presence of fossil valleys was identified along the following tributaries: （Fig. 3.2）

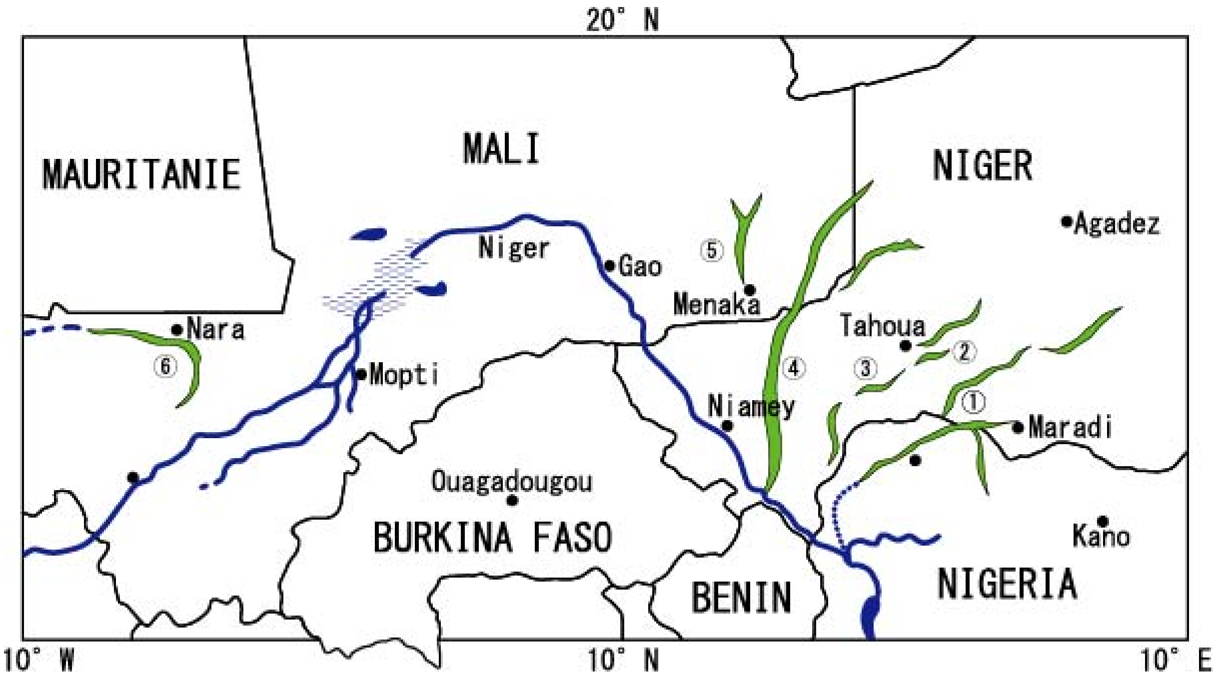
- Goulbin Kaba and Tarka Valley (Maradi, Niger, and Sokoto, Nigeria)
- Souma Valley (the south-eastern part of Tahoua, Niger)
- Dallol Maouri (Dan Doutchi and the western part of Tahoua, Niger)
- Dallol Bosso (the eastern and the north-eastern part of Niamey, Niger)
- Ezgueret River (Menaka, Mali)

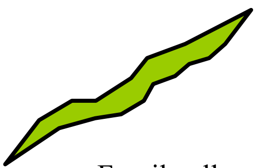
The presence of fossil valleys was also identified in the Senegal River basin along the following tributary:

- Serpent Valley (Nara, Mali)

In general, there are *wadis* (temporary rivers that appear only in the rainy season) on the current ground surface of these fossil valleys. These fossil valleys on the current ground surface are huge compared with the discharge of the current *wadis*. They are several kilometers, or even several tens of kilometers in certain cases. Among fossil valleys that flow into these large fossil valleys, there might be small or medium-size fossil valleys that are suitable for subsurface dams.

This study suggests that there may be fossil valleys of suitable size for subsurface dams buried beneath current rivers in the eastern and the north-eastern part of Burkina Faso, a part of the Niger River basin. In the survey to select the project site, the potential existence of such fossil valleys in the central and the northern part of Burkina Faso was focused on.





Fossil valleys

① Goulbin Kaba, Tarka Valley
② Souma Valley
③ Dallol Maouri
④ Dallol Bousso
⑤ Ezgueret River
⑥ Serpent Valley (tributary of the Senegal River)

Fig. 3.2: Distribution of fossil valleys in Nigeria and Mali

Note: The above "fossil valleys" were identified by the Sahel Greenbelt Study Group of Japan in 1989 and 1990. In fact, there may be more fossil valleys.

3-4 Surveys carried out in this project

3-4-1 Interpretation of satellite images and aero-photographs

Satellite images and aero-photographs are useful means of examining the physical conditions (landform, geology, surface water, vegetation, etc.) of vast areas. They are particularly valuable in surveying flat relief areas without precise topographical maps like Africa.

In this project, satellite images and aero-photographs were interpreted to identify appropriate sites for subsurface dams.

(1) Landforms considered as appropriate sites for the subsurface dam
In the interpretation of satellite images and aero-photographs, the following landforms were considered:

1) Landforms suggesting the potential presence of fossil valleys: These are landforms with excessively wide flood plains, whose line is similar to that of the current rivers (*wadis*, in many cases), compared with the discharge of current rivers (*wadis*).
2) Ring-shaped landforms: These are landforms whose ridges range in a ring shape with a gapped part due to denudation. These landforms are often observed in the area of volcanic rock. Groundwater recharged with rainfall within these landforms converges at the gapped part.
3) Bottleneck-shaped landforms: These are landforms with a bottleneck part of the basement rock, buried by unconsolidated sediment, possibly accompanied by underflow water.

(2) Procedure for interpretation
First, false color photographs on a scale of 1/200,000 or 1/500,000 were made from LANDSAT TM (Thematic Mapper) images covering the central or the northern part of Burkina Faso. On the basis of the interpretation of these satellite images, 13 sites were identified as having potential geomorphological and geological structures appropriate for a subsurface dam.

Next, preliminary exploration in a large area including these 13 sites was carried out. As a result, 6 sites were selected, excluding sites with the following problems:

- Estimation of the underground structure was difficult, or the scale of the underground structure was too large for the model project.
- Access from the capital, Ouagadougou, was too difficult.
- Many other projects already existed.

Detailed landform classification maps were then drawn from black and white aero-photographs on a scale of 1/20,000 or 1/50,000 that covered the selected 6 sites. As the result of this process, 6 sites were narrowed down to 5.

It is recommended that aero-photographs be used for the interpretation of limited areas because the resolution of the LANDSAT images is low and the geomorphological and geological structures interpreted from them tend to be biased toward larger ones.

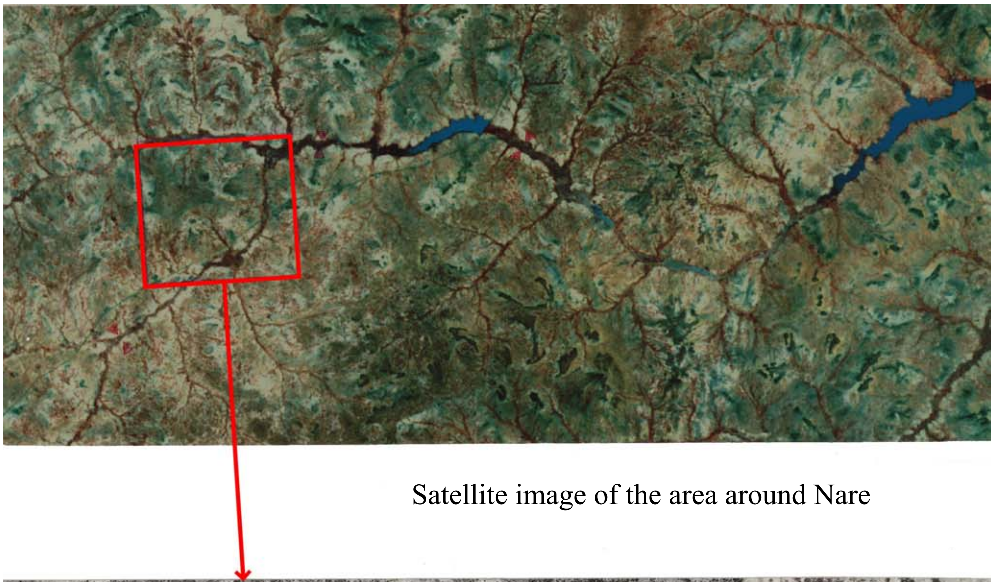
(3) Results of the selection of possible sites

The results of the selection of possible sites for a subsurface dam by the interpretation of the satellite images and aero-photographs and preliminary exploration are summarized in Table 3.1.

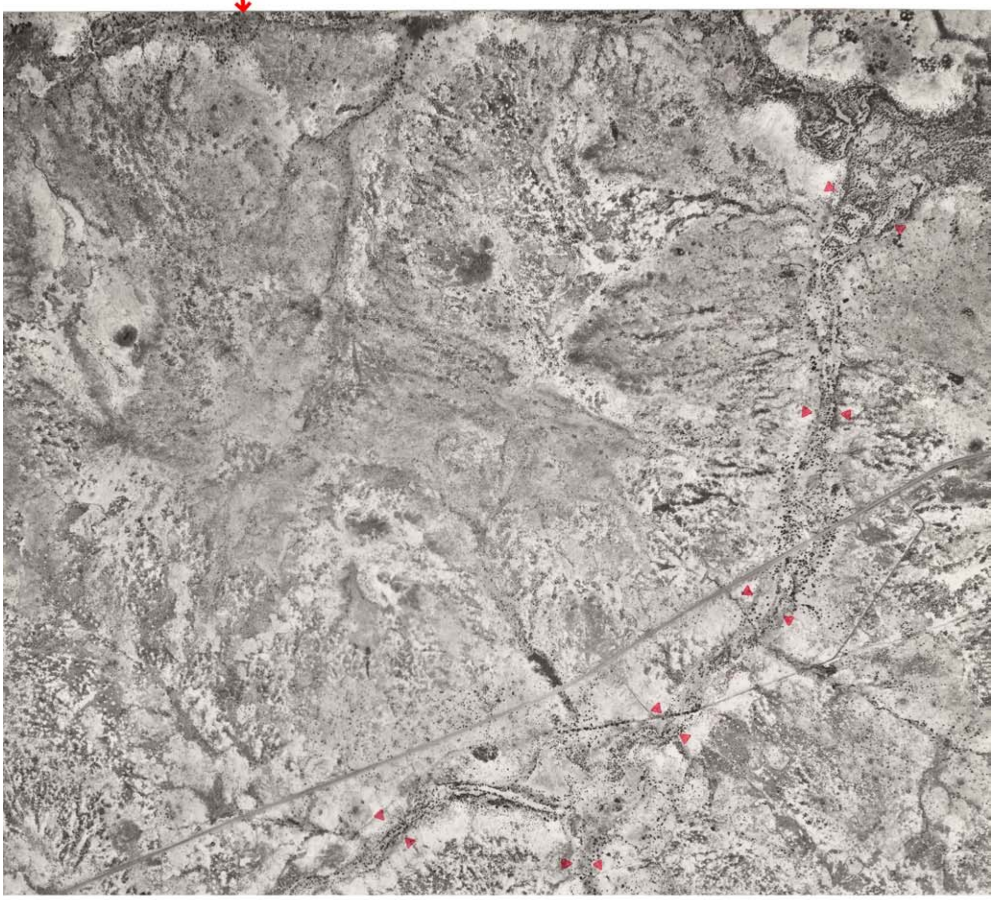
Table 3.1: Results of the selection of possible sites for a subsurface dam by the interpretation of satellite images and aero-photograph and preliminary exploration

Regions preselected from LANDSAT images			Results of preliminary exploration (Reason for rejection)	Results of interpretation of aero-photographs (Reason for rejection)
Name of province	Name of village	Checked landform		
Oudalan	Saouga	Fossil valley	Possible	Possible
Seno	North of Dori	Fossil valley	Impossible (The zone could not be identified.)	—
Seno	Yakouta	Fossil valley	Impossible (The structural scale was too large.)	—
Seno	Gangaol	Fossil valley - *wadi*	Possible	Impossible (The catchment area was too small.)
Namentenga	Nare	Fossil valley	Possible	Possible
Sanmatenga	Kouloga	Bottleneck	Impossible (The unconsolidated sediment layer might be too thin.)	—
Sanmatenga	Louda	Ring-shaped	Possible	Possible
Sanmatenga	Bassneile	Ring-shaped	Possible	Possible
Sanmatenga	Tangapore	Bottleneck	Possible	Possible
Sanmatenga	Balou	Bottleneck	Impossible (Poor access)	—
Sanmatenga	Santabe	Bottleneck	Impossible (Poor access)	—
Bam	Around Loga	Ring-shaped	Impossible (Many projects had already existed.)	—
Yatenga	North of Gongoure	Bottleneck	Impossible (Poor access)	—
Yatenga	North of Ban	Special reason *	Impossible (Poor access)	—

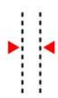
Note: It was requested by S.P.CONAGESE that the subsurface dam be constructed here because of the threat of forest extinction.



Satellite image of the area around Nare



Aero-photograph of the area around Nare



Fossil valley

Fig. 3.3: Satellite image and aero-photograph of the "fossil valley"

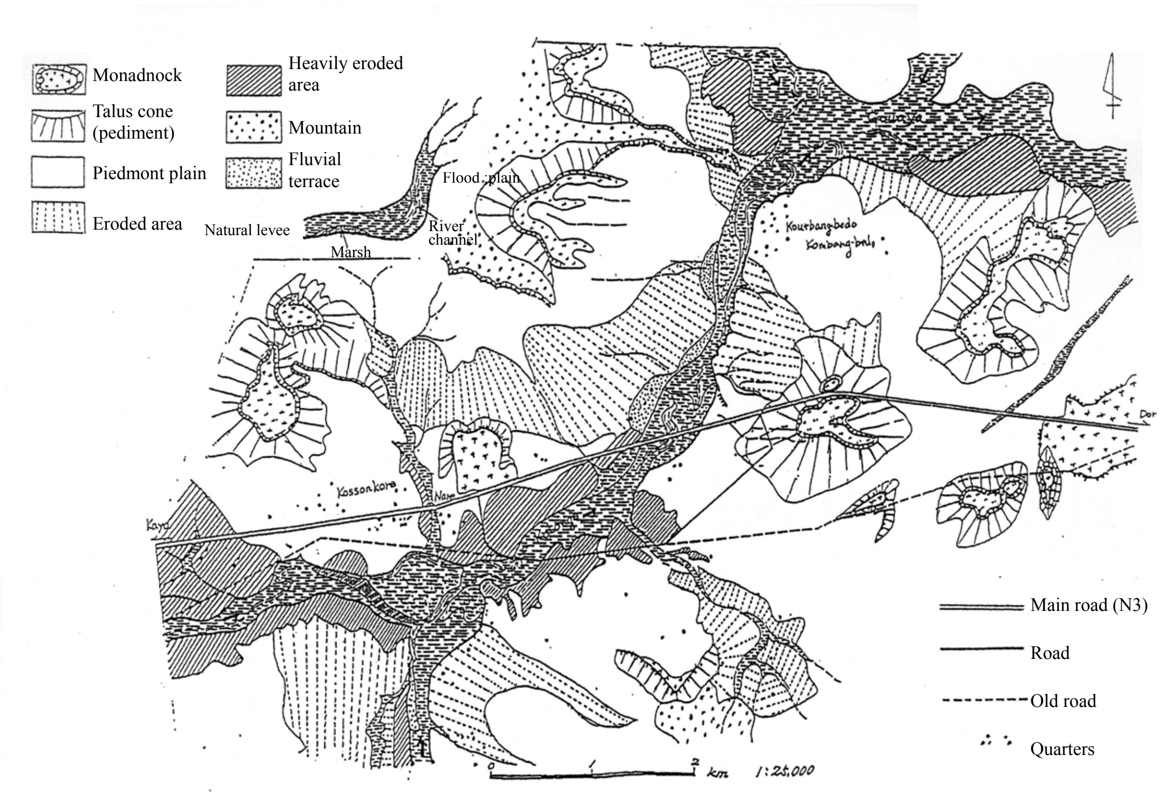


Fig. 3.4: Sample of landform classification maps based on aero-photographs (area around Nare)

3-4-2 Field exploration

At the 5 sites selected by interpreting the satellite images and aero-photographs and preliminary exploration, a detailed field exploration was carried out to assess the feasibility of constructing a subsurface dam, also taking into account the results of the electric soundings mentioned below (see Section 3-4-3).

During the field exploration, the following surveys were carried out, and the distribution of villages was grasped.

(1) Grasping landform and geology
The landform and geology of the sites were grasped to detect the presence of shallow groundwater and to estimate its structure.

In these surveys, the landform classification maps drawn from aero-photographs were used as topographical maps and preliminary examination charts. Indeed, in surveying an area where flat relief predominates without precise topographical maps, it is sometimes impossible not only to understand the geomorphological significance of the phenomena observed in the field, but also to confirm the present location, without these land classification maps or aero-photographs themselves.

(2) Survey of existing wells
To grasp the presence of groundwater, the following surveys of existing wells were carried out. In these surveys, most of the useful information was obtained from “dug wells” whose side walls were not covered by concrete.

1) Confirmation of the locations of the wells, and landform and geology
2) Measurement of the groundwater level in the wells
3) Confirmation of seasonal fluctuation in the groundwater level by listening to inhabitants
4) Confirmation of geology of the aquifer and its upper strata by observation of the interior of the wells and the surplus soil produced by digging, as well as by listening to inhabitants

(3) Confirmation of the distribution of unconsolidated sediment
Grasping the distribution of unconsolidated sediment that can form aquifers of shallow groundwater was attempted. When it was difficult to directly grasp their distribution, it was estimated from the distribution of the outcrop of the basement rock, which was grasped by careful survey, of the lateritic crust in particular.

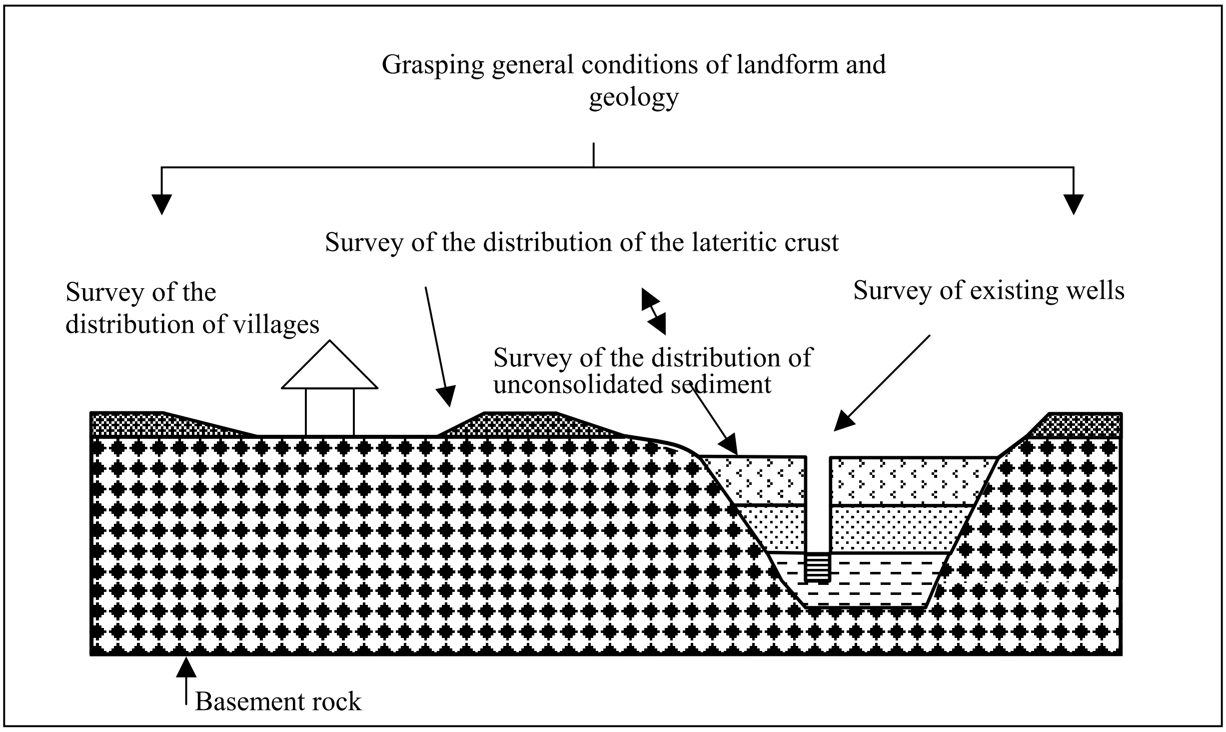


Fig. 3.5: Points of field exploration

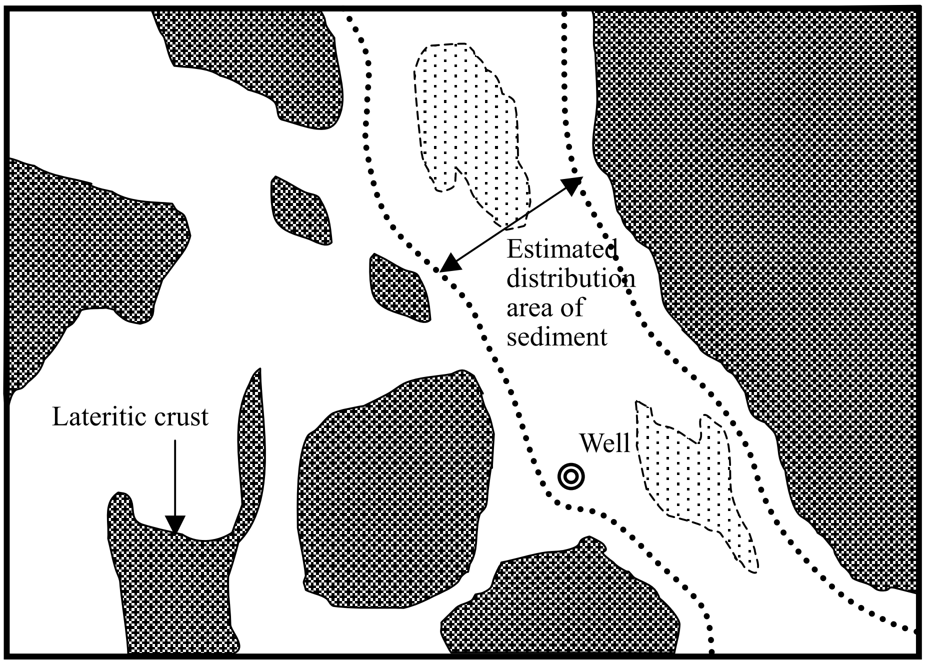


Fig.3.6: Relation between the distribution of the lateritic crust and unconsolidated sediment

3-4-3 Geophysical survey

At the 5 sites selected by the interpretation of satellite images and aero-photographs and preliminary exploration, electric soundings were carried out in addition to field exploration to determine the geological structure.

At some sites in Tangapore Village and Nare Village, magnetic soundings were also carried out, whose results only confirmed those of the electric soundings but with less precision. The electric soundings are thus more useful for detecting underground structure at a shallow depth.

(1) Method of electric soundings
The electric soundings were carried out using the vertical quadripole method (Wenner's method). From their results, resistivity profiles were drawn to analyze the underground structure. One of the resistivity profiles thus obtained is shown in Fig. 3.7.

For the electric soundings and the analysis of their results, the following points were taken into account.

1) Survey lines for the resistivity profiles, whose length was about 150 to 500 m, were set across the assumed underground structure. Along the survey lines, the electric soundings were carried out with an interval of about 50 to 100 m, namely 3 to 10 survey points per line.

2) At each survey point, a sounding line was drawn parallel to the direction of the supposed underground structure.

3) To obtain a three-dimensional view of the geological structure, 2 to 3 survey lines for the resistivity profiles were set as far as possible.

4) The resistivity of the basement rock (lateritic crust, heavily weathered rock, and fresh rock) were determined by lengthening the survey lines to an outcrop of basement rock or to a point where basement rock was definitely present at a very shallow depth. These resistivities determined largely contributed to the geological interpretation of the resistivity profiles.

5) Where there were wells (in particular "dug wells") allowing observation of the groundwater level and geological sections, electric soundings were also carried out near the wells to determine the resistivity of the well site. These resistivities increase the certainty of the geological interpretation of the resistivity profiles.

Resistivity determined by electric soundings reflects not only the electrical properties of the rock and soil, but also those of the groundwater. Even in the strata composed of identical materials, resistivity may vary remarkably if there is a large difference in their water content. Therefore, resistivity is not sufficient for precisely determining the lithological nature of the strata. However, resistivities and resistivity profiles obtained from electric soundings carried out at a large number of points are important clues in estimating the geological structure and the state of groundwater because zones of almost identical resistivity can be considered to correspond to strata with identical lithologies and water content.

(2) Selection of the subsurface dam sites based on the electric soundings

The results of the examination of the geological structure of each of the 5 sites on the basis of the field exploration and the electric soundings were as follows:

a. Saouga (south of Gorom Gorom, Oudalan Province)
This site probably had a fossil valley that was an aquifer of shallow groundwater. However, the construction of the subsurface dam would be too large as a demonstration study.

b. Nare (south of Tougouri, Namentenga Province)
This site probably had a fossil valley that was an aquifer of shallow groundwater. Although constructing a subsurface dam here would be a little too large as a demonstration study, the site was suitable for a subsurface dam.

c. Louda (south of Kaya, Sanmatenga Province)
A ring-shaped landform had been formed at this site, but no favorable aquifer was discovered.

d. Bassneil (north of Korsimoro, Sanmatenga Province)
A ring-shaped landform had been formed at this site, but an unconsolidated sediment layer that could have been an aquifer was likely to be very thin.

e. Tangapore/Kossoden (north of Korsimoro, Sanmatenga Province)
This site was of a bottleneck-shaped landform located downstream of a ring-shaped landform, and the presence of shallow groundwater was suggested by the results of the survey of existing wells. The resistivity profiles by electric soundings also indicated the possible presence of a fossil valley whose size was appropriate for a demonstration study. This site was thus probably suitable for a subsurface dam site.

As a result of the survey described above, 2 sites were selected as candidates for the subsurface dam site: Tangapore Village, Korsimoro District, Sanmatenga Province, and Nare Village, Tougouri District, Namentenga Province.

The number of electric soundings carried out at these 2 sites were as follows:

- at Tangapore: 58 points on 4 survey lines
- at Nare: 95 points on 6 survey lines

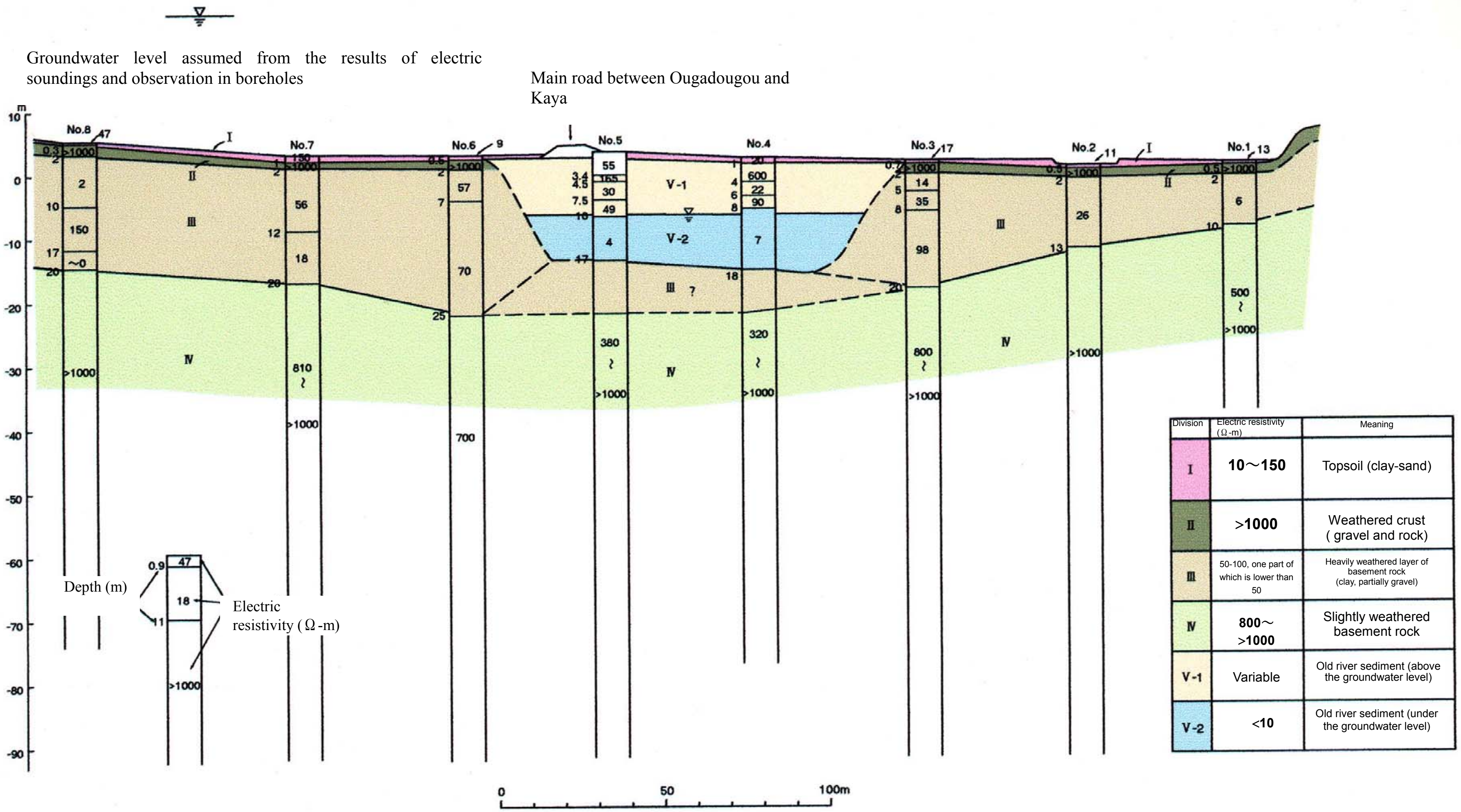


Fig. 3.7-1: Resistivity profile at the north of Korsimoro - point C (Tangapore)

Fig. 3.7: Resistitivity profiles based on the electric soundings

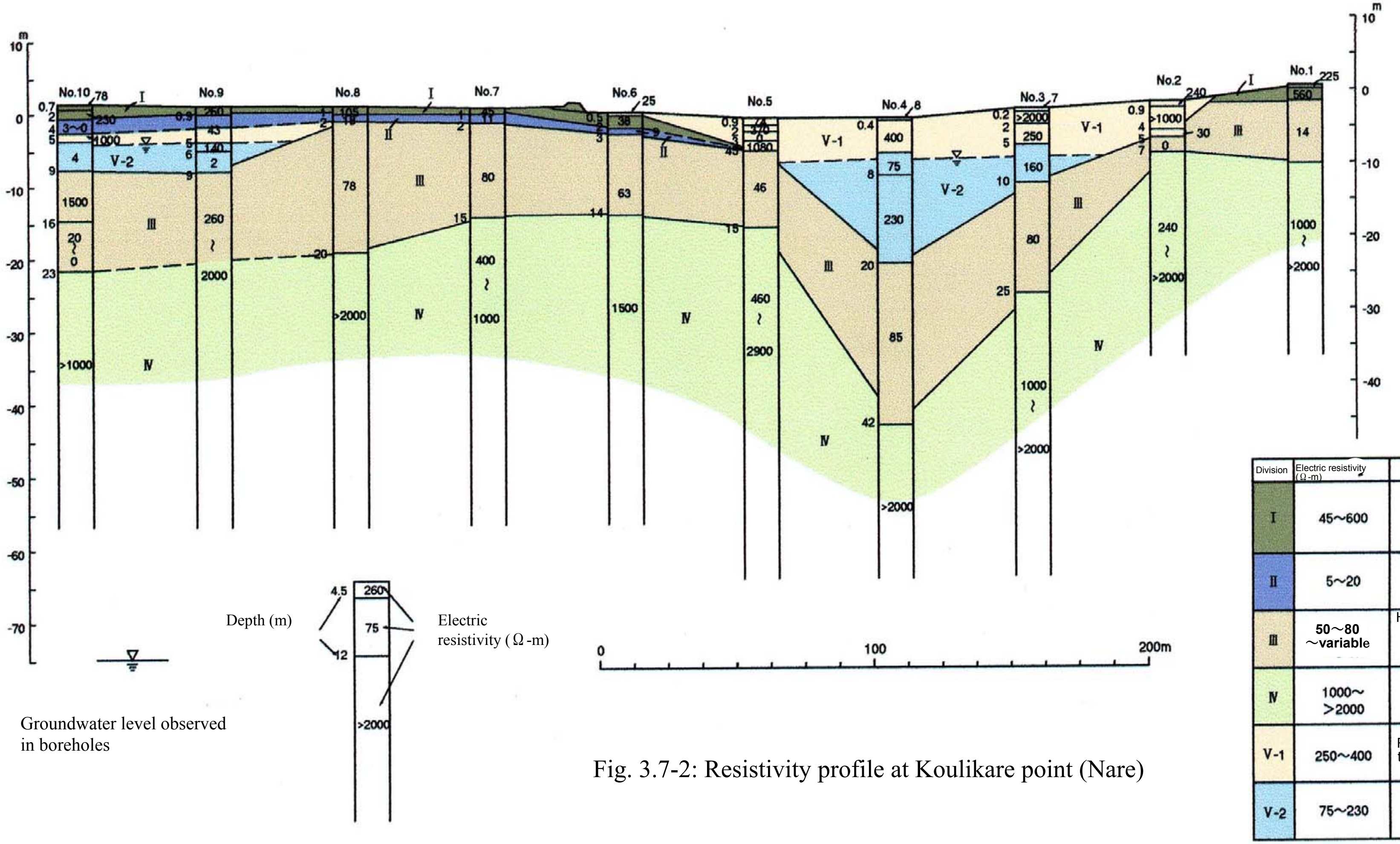


Fig. 3.7-2: Resistivity profile at Koulikare point (Nare)

Division	Electric resistivity (Ω-m)	Meaning
I	45～600	Topsoil - weathered crust
II	5～20	Moist layer under the topsoil
III	50～80 ～variable	Heavily weathered layer of basement rock (clay, partially gravel)
IV	1000～ >2000	Slightly weathered basement rock
V-1	250～400	River sediment (above the groundwater level)
V-2	75～230	River sediment (under the groundwater level)

3-5 Detailed field surveys (test drillings, permeability tests, and observations of groundwater level)

At the two sites (Tangapore and Nare) selected on the basis of the results of the field exploration and the electric soundings, the following detailed field surveys were carried out to confirm the geological structure, to identify hydrogeological characteristics and to estimate rainfall within the drainage basin.

- Test drillings
- Permeability tests in boreholes
- Observations of the groundwater level in boreholes

In parallel with these surveys, meteorological observations (see Section 6-2) and a socio-economic study were carried out (see Section 3-6).

(1) Test drillings
To confirm the geological structure estimated from the results of the electric soundings, test drillings were carried out along the survey lines of the electric soundings.

In this project, boreholes were drilled using a drilling machine for deep wells, and rubble samples (slime) taken during drilling were used to estimate the geological structure. However, it was particularly difficult to distinguish the heavily weathered basement rock (argillized part) from the clayey or silty layers of fluvial deposits. Therefore, it is preferable, for at least half of the boreholes, to use a test drilling machine for geological survey that enables the collection of undisturbed samples.

The number of boreholes was as follows:

- at Tangapore: 3 boreholes of 60-m depth, 3 boreholes of 20-m depth
- at Nare: 2 boreholes of 60-m depth, 19 boreholes of 20-m depth

(2) Permeability tests in boreholes
To determine the permeability of the ground, permeability tests were carried out in the boreholes.

The tests were carried out by observing the lowering speed of the water injected into the boreholes using a tank-lorry or jerry cans to obtain the permeability coefficient of the ground according to the depth. The permeability tests were carried out in:

- 3 boreholes at Tangapore
- 12 boreholes at Nare

(3) Observations of groundwater level in boreholes
To determine seasonal fluctuation in shallow groundwater level, observations of groundwater level were carried out in 3 boreholes at Tangapore and 5 at Nare.

The groundwater level was measured irregularly using a manual water-level sounder at Tangapore, whereas it was measured continuously with automatic water level recorders at Nare.

The observation was carried out for about 6 months before the final selection of the subsurface dam site (from the middle of the rainy season to the first half of the dry season).

However, a longer period of observation is desirable, given the considerable seasonal and annual fluctuation in groundwater level. In addition, as described below in Section 6-4, there is a risk that the level of perched water is mistaken for that of the real groundwater. Therefore, attention should be paid to the observation method of groundwater level.

From the results of the test drillings, permeability tests and observations of the groundwater level, the hydrogeological characteristics of the 2 candidate sites, Tangapore and Nare, were estimated as follows (see also Fig. 3.8 and Fig. 3.9):

Tangapore
The results of the electric soundings suggested the presence of a fossil valley. However, the test drillings did not reveal fossil valley sediment (fluvial deposits). No geological difference was observed between the inside and outside of the supposed fossil valley. The groundwater levels of the inside and outside were almost the same, and seasonal fluctuation in the groundwater level of the inside and outside corresponded with each other. Namely, between the inside and outside of the fossil valley assumed from the results of the electric soundings, there was no obvious geological difference, and hydraulic continuity was practically ensured. This shows that there is no fossil valley at Tangapore.

The reason the electric soundings suggested the presence of a fossil valley was probably the presence of a large fracture zone in the basement rock.

Nare
All the results of the examination of the surplus soil produced by digging of the existing wells, of the electric soundings and of the test drillings showed the presence of a fossil valley beneath the Kolongo River at Nare. The permeability coefficient determined by the permeability tests were 10^{-3} to 10^{-4}cm/sec inside the fossil valley and 10^{-5} to 10^{-6}cm/sec at the valley sides. This shows a geological structure in which the permeable fossil valley sediment is surrounded by impermeable basement rock. In addition, the presence of groundwater was confirmed inside the fossil valley, with no groundwater outside the fossil valley. It was thus deduced that the fossil valley constitutes a groundwater channel.

The observation of groundwater level inside the fossil valley showed seasonal fluctuation in the groundwater level between the rainy season and the dry season, indicating the large fluidity of groundwater.

Figure 3.8 and Fig. 3.9 are schematic figures showing the results of the detailed field surveys.

The site assumed suitable for the subsurface dam, a narrow part of a fossil valley, was immediately upstream of the point where the Kolongo River flowed into its trunk, the Gouaya River. There was thus little risk that the construction of the subsurface dam would "exhaust the groundwater in the downstream area".

All these results showed that Nare Village is hydrogeologically best as a subsurface dam site.

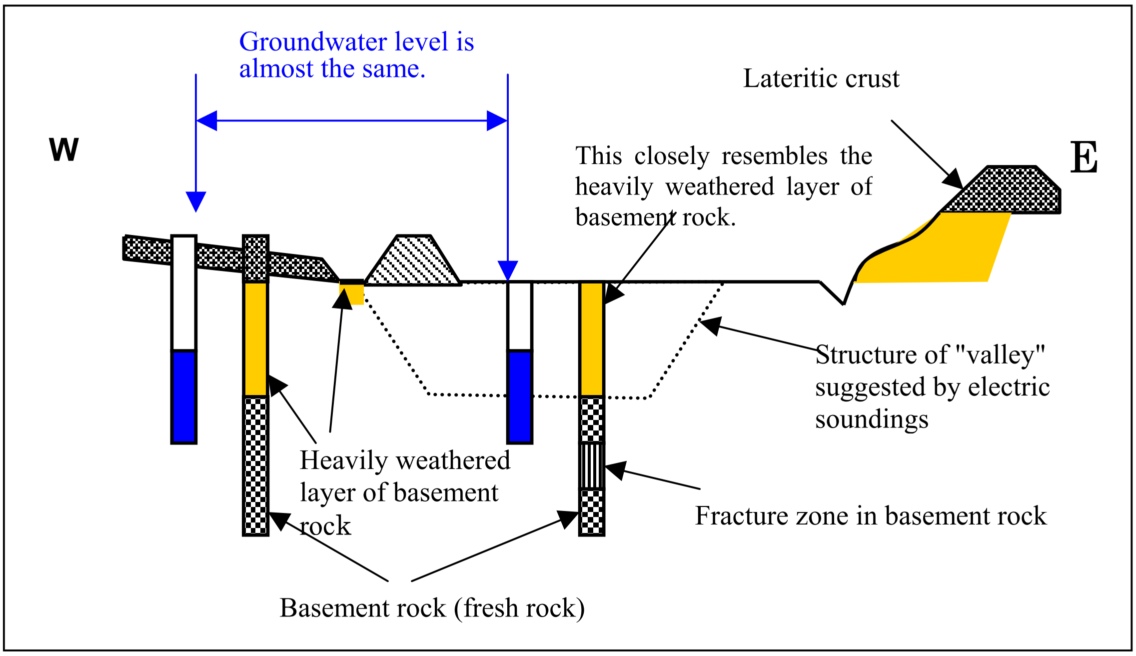


Fig. 3.8: Schematic diagram of the results of the detailed field survey at Tangapore

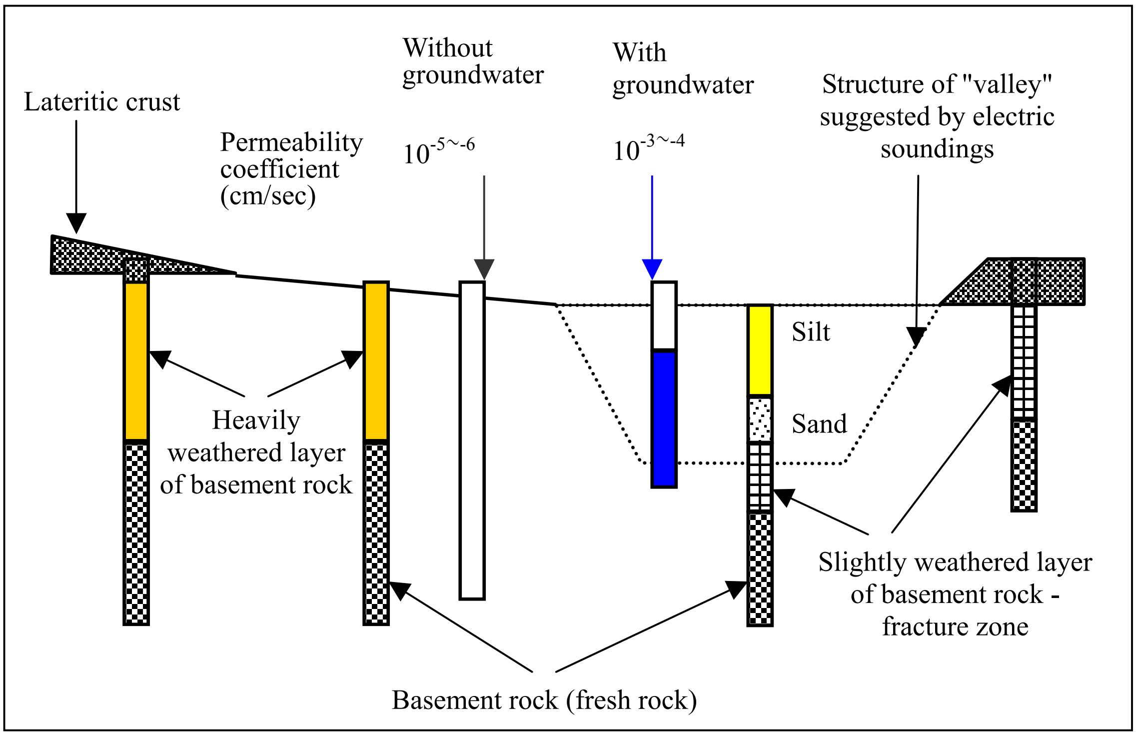


Fig. 3.9: Schematic diagram of the results of the detailed field survey at Nare

3-6 Socio-economic study

As a part of the field survey, a socio-economic study was also carried out at Tangapore and Nare.

A summary of the results of the study is as follows:

Tangapore

- Population: 2,079, all Mossi people
- Public services: One primary school (built in 1995), no dispensary
- Main activities for living: Agriculture, with livestock farming as secondary. Commerce is also active in the market (Korsimoro).
- Common diseases: Meningitis, eye diseases, headaches, tumors, diarrhea, etc.
- Annual average rainfall: About 660 mm until 1995

The village is located in the transition zone between low mountains and peneplain. Not only the peneplain but also the gentle mountain slope are cultivated, and the arable land is exploited almost to the limit. Due to the use of fertilizers in some parts, the food self-sufficiency rate is estimated to be more than 90%. However, considering the situation that no more arable land remains and the land has continued to degrade, the village is likely to suffer serious food shortage with the increase in population in the near future. It is thus primarily important to increase the productivity of the land, and to exploit new water resources for it.

Livestock farming is the secondary activity for living in this village, and has a role of "savings" to prepare for emergency situations such as drought. However, a shortage of pasture and a lack of water for animals in the dry season are problems for this activity.

There were 3 hand pumps, 6 dug wells, 1 small-scale surface dam and 6 reservoirs in the village, but it was estimated that only about 70% of the water demand (about 20 liters per person) for domestic use was supplied. The water in the small-scale surface dam and reservoirs used by livestock animals was also used by the villagers for domestic use, and this situation led to diseases caused by polluted water. Therefore, to improve water quality for domestic use, the exploitation of new water resources was necessary.

Some young villagers in Tangapore had formed a group to undertake the modernization of agriculture, and they were trying to produce compost and to grow some vegetables. Tree-planting education was also promoted in the primary school. Although the lack of water constrained these activities, the will, experience and recognition of the villagers will facilitate their participation in this project that will aim mainly at the effective use of groundwater resources.

Nare

- Population: 2,896, mostly Mossi people with some Fulani people
- Public services: One primary school (built in 1996), no dispensary
- Main activities for living: Agriculture, with livestock farming as secondary (It is the principal activity for Fulani people.)
- Common diseases: Guinea worm infections, eye diseases, dysentery, meningitis, etc.
- Annual average rainfall: About 590 mm until 1995

The village is on a peneplain with some small monadnocks, and the Kolongo River, a tributary of the Gouaya River that is a part of the Niger River basin, runs through the village. The Kolongo River is a *wadi*, a seasonal river that has running water only in the rainy season.

The peneplain and the lowland along the Kolongo River (part of which is flood plain) are exploited as farmland. However, the farmland is only 12% of the territory, and arable land remains. Forest covers only 2% of the territory. Most of the bare land, which occupies about 20% of the territory, was cultivated before. It probably means land degradation has continued due to the cutting and the cultivation of forest and bush.

The farmland is in general barren. Not using either fertilizer or compost, the food self-sufficiency rate in Nare Village is only about (or less than) 60%, which makes the village one of the poorest in Burkina Faso. Many livestock animals, especially cattle, can be seen, but most of them belong to the Fulani people. Few Mossi people keep livestock animals in sufficient number as "savings" for emergencies like drought.

Nare Village, including Kombangbedo Village, did not have sufficient modern water-supply facilities. It had only 1 hand pump and 5 dug wells with concrete rims. Water supply by these facilities was estimated to be less than 60% of the demand. Most of the villagers obtained water for domestic use in the rainy season from the river, and in the dry season, from the dug wells excavated in the flood plain. This led to a high incidence of disease such as Guinea worm infestation caused by polluted water. Many villagers wanted to grow some vegetables to prepare for food shortages and also to obtain a cash income. However, under conditions that did not even allow sufficient water for domestic use, there was only one family who were actually growing vegetables.

Under these circumstances, the villagers of Nare had a strong desire to exploit new water resources. However, they did not have the information required to improve their living conditions or for rural development, and their participation in the model project was expected to be difficult.

The results of the above-mentioned socio-economic study suggest that Tangapore Village was more ready for the project.

However, as described in Section 3-4, it is Nare that has the hydrogeological structure appropriate for a subsurface dam. Finally, it was decided that the model project would carried out at Nare because the feasibility of construction of the subsurface dam was the first priority.

4. Construction of a subsurface dam

4-1 Methods of construction of a subsurface dam

The various construction methods of a subsurface dam are listed in Table 4.1.

In some countries including Japan, there have already been several examples of subsurface dams. The majority of them were constructed by a method known as "cut-off wall by underground diaphragm wall (e.g. soil-cement mixing wall method)". Theoretically, a subsurface dam utilizes a "cut-off wall" for groundwater storage, and can be built using the “cut-off wall” method appropriate for local conditions.

Table 4.1: Methods of construction of a subsurface dam

Category	Type of construction method	Construction method and structure	Features
Application of method of cut-off wall under ground	Wall of steel sheet	Piling steel sheets continuously	This method is suitable for weak ground, but piling into gravel layers or basement rock is difficult.
	Wall of steel tubing	Piling steel tubes continuously	
	Underground diaphragm wall	Casting reinforced concrete wall on-site	There are various methods according to the ground conditions. They all require highly sophisticated equipment.
	Column-type underground diaphragm wall	Casting wall of mortar piles continuously on-site	This method was used to construct the subsurface dam at Miyako Island in Japan. It requires highly sophisticated equipment.
Application of ground improvement method	Grouting method	Injection of mortar into boreholes drilled intermittently	This method was partially used in the construction of the subsurface dam at Miyako Island. It is widely applicable because small and medium-size equipment can be used. However, confirmation of the effect of water cut-off is somewhat difficult.
Application of general dam construction method	Method of concrete dam construction	Structure of concrete dam under ground fully or by half (excavation/construction of dam body/filling back)	This is suitable for the "torrent dam"-type subsurface dam whose crest is exposed above the ground surface (there are some examples in countries such as Kenya). The construction costs are higher than those of the "earth dam"-type subsurface dams. Countermeasures against water leakage are required. For deep excavation, the costs would be too high.
	Method of earth dam construction	Structure of earth dam under ground	This method was used for this project. Dams of this type can be constructed using ordinary civil engineering equipment, and construction management is easy. However, countermeasures against water leakage are required. For deep excavation, the costs would be too high.

In this project at Nare, the "earth dam" method shown at the bottom of Table 4.1 was adopted for the following reasons:

1) The "fossil valley" was buried deep (about 8 m below the ground surface), and it had almost no groundwater run-off in the dry season. It was thus possible to apply this method.

2) This method does not require sophisticated machines and could be carried out with those available in Burkina Faso.

3) The cost of construction, including transportation and rental of machines, was the lowest.

4-2 Characteristics of the subsurface dam built at Nare

The characteristics of the subsurface dam built at Nare for this model project are as follows:

(1) Site
In the fossil valley in the Koulikare Quarter, Nare Village, Tougouri District, Namentenga Province, Burkina Faso

(2) Structure of the dam body
"Subsurface earth dam" (see Fig. 4.1)

- Depth of the base: 3.0 m to 11.4 m below the ground surface (maximum height of the dam: 8.4 m)
- Crest length: 216.3 m
- Width (thickness): 8.6 m at the base, 3.0 m at the crest
- Volume: 7,144 m^3
- Filling materials: clayey silt (heavily weathered layer of basement rock)
- Permeability coefficient: 10^{-7} to 10^{-8} cm/sec (very partly, 10^{-6} cm/sec)

At the upstream side of the base of the dam, an "anchor key" with about a 3- to 4-m width and a 1.5-m depth (protrusion into the basement rock) was formed to protect the base. At a level just above the crest, about a 1-m-thick layer of gravel with a similar diameter was laid to ensure good permeability.

(3) Water source of the subsurface dam reservoir
Shallow groundwater within the fossil valley buried along the Kolongo River, a tributary of the Gouaya River that is a part of the Niger River basin

(4) Dimensions of reservoir

- Maximum extent of reservoir area: 13.4-km length, about 150-m average length (lowest estimate), about 2-km^2 area
- Volume of reservoir layer: About 9,000,000 m^3 (estimate)
- Water storage capacity: About 1,800,000 m^3 (estimate)

(5) Amount of construction work

- Excavation: Excavation of soil: 51,213 m^3, excavation of rock: 4,377 m^3, total: 55,590 m^3
- High-density filling (the dam body): 7,144 m^3

- Medium-density filling (upstream and downstream sides of the dam): 26,662 m^3
- Low-density filling (above the dam): 21,814 m^3

(6) Used machines
- Bulldozers: 2 to 3 units
- Backhoes: 1 to 2 units (excavators)
- Trucks: 2 to 3 units (dump trucks)
- Rollers: 1 to 2 units (Komatsu JV100)

(7) Duration of construction
From 15 November 1997 to the end of June 1998. This period included the construction of other experimental facilities, and the actual duration devoted to the construction of the subsurface dam was about 4.5 months.

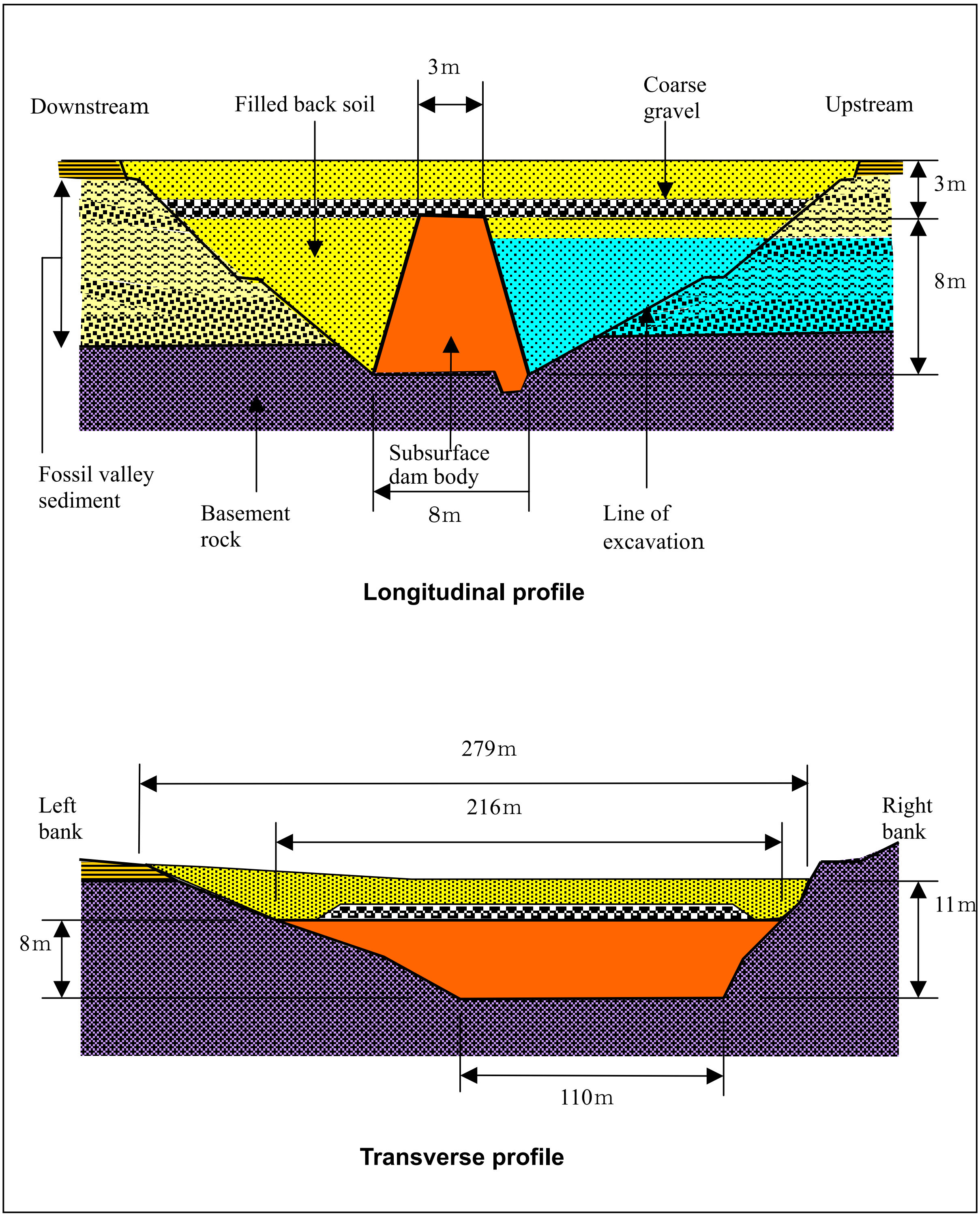


Fig. 4.1: Schematic diagram of the structure of a subsurface dam

4-3 Construction of the subsurface dam

(1) Excavation

The construction of a subsurface dam requires much larger excavation than the size (length, width, depth) of its body. Excavation for construction site access roads is also necessary.

In the case of the subsurface dam in Nare, the scale of the excavation was as follows:

- Length: 307.1 m (including the excavation for construction site access roads)
- Width: 50 m maximum
- Depth: 12.9 m maximum
- Total amount of excavation: 55,590 m^3

The total amount of excavation was thus 7.8 times as much as the volume of the dam.

During excavation, the following difficulties had to be dealt with:

1) Although the excavation was carried out during the dry season when the groundwater decreased in the fossil valley, it encountered difficulties due to water springing from the sandy layers at an intermediate depth of the fossil valley sediment or from the boundary between the sediment and the basement rock. Because subsurface dams are constructed across shallow groundwater channels, this water springing during the construction is not rare. It is thus necessary to pay sufficient attention to the choice of season and the construction method.

2) On the right bank, the buried structure of the fossil valley proved to be the same as that estimated from the preliminary survey, but on the left bank, the fossil valley extended beyond the estimated limit. In general, the results of the preliminary survey are not always completely accurate, and the participation of geologists experienced in supervising construction is thus very important.

(2) Construction of the dam body

As the material of the dam body, the heavily weathered layer of basement rock (clayey silt), which was extracted 300 m from the dam site, was used.

Before the construction of the dam body, filling and pressing tests with the material were carried out to establish quality control standards for filling:

- Thickness of spread layer per filling: 30 cm
- Thickness of pressed layer per filling: 25 cm
- Number of pressings: 6 back-and-forth passes with Komatsu roller JV100
- Water content of the material before filling: Optimal water content ± 1%
- Dry density of the pressed layer: Higher than 90% of the maximum dry density
- Permeability coefficient of pressed layer: Lower than 10^{-5}cm/sec

After excavation down to basement rock of the fossil valley, filling the dam body was carried out according to the quality control standards described above. In the process of filling, the following quality tests were carried out:

- Tests of the water content of the material: 52 layers, 130 points in total
- Tests of the dry density of the pressed layers: 52 layers, 130 points in total
- Measurements of the permeability coefficient of the pressed layers: 12 layers, 38 points in total

All the results of the quality tests were good and satisfied the standards. The permeability coefficients of the pressed layers were about 10^{-7} to 10^{-8}cm/sec (10^{-6}cm/sec at only 2 tests out of 38), which were much better than the required value.

It should be remembered that the foot and base of the dam must protrude into basement rock of the fossil valley to prevent water leakage.

As stated above, the material of the dam body was extracted from the heavily weathered layer of basement rock (argillaceous silt) located about 300 m from the dam site. However, surplus soil (fossil valley sediment) produced by excavation at the dam site might be usable as the material of the dam body. Such re-use would reduce "the devastated area" by the construction of the subsurface dam. For future "subsurface earth dam" projects, it is thus recommended to survey in detail the geological nature of the dam site from this viewpoint as well.

(3) Backfilling of the excavation
Parallel to the construction of the dam body, the excavated space of both the upstream and downstream sides of the dam body was backfilled. The backfilled portion was pressed by 3 back-and-forth passes with Komatsu roller JV100.

The excavation was initially backfilled to the crest level of the dam. Then, to obtain good permeability, gravel with a similar diameter was laid about 1 m thick, followed by additional backfilling (also pressed by 3 back-and-forth passes with the roller).

As the dam body was made of material from the other site, surplus soil, the amount of which was almost equivalent to the volume of the dam, was left after backfilling. This surplus soil was used to fill back the site from which the material of dam body was extracted.

(4) Treatment after construction
After backfilling was completed, the landform of the dam site was almost restored. However, restoring the natural vegetation was so slow that the ground remained bare for about two years after the dam construction. To protect the natural vegetation from possible grazing by livestock animals, a wire fence was set around the construction site and *Acacia senegal* was planted within it in 2001. The rate of survival was about 60% (in January 2002), but plenty of natural vegetation was growing and the construction site had the appearance of shrub forest.

Photo 4.1: Construction of the subsurface dam -1

Photo 4.2: Construction of the subsurface dam -2

Photo 4.3: Construction of the subsurface dam -3

Photo 4.4: Construction of the subsurface dam -4

5. Structure of the "fossil valley" at Nare

The excavation for the construction of the subsurface dam at Nare revealed a whole section of the "fossil valley" and thus made it possible to study its structure in detail. Fossil valleys are frequently found in West Africa, in particular in the Niger River basin where some test drillings have already been conducted. However, this project was probably the first example of direct inspection of the structure of a fossil valley through a full-section excavation.

The information obtained at the subsurface dam site is as follows. A geological cross-section of the fossil valley is shown in Fig. 5.1.

(1) Shape of the "fossil valley"
The revealed fossil valley had a width of about 130 m at its bottom and about 180 m at the top of its side slopes. The bottom of the valley was not flat, but slightly undulating in the shape of "W". Its depth varied from 5.9 m at the shallowest part around the center of the bottom to 8.3 to 8.5 m at the deepest part.

The side slope of right bank was relatively steep with a declination of about 30 degrees, whereas the declination of the side slope of left bank was between 9 and 10 degrees.

This fossil valley was thought to be buried along the present Kolongo River.

(2) Characteristics of the "fossil valley sediment"
The sediment that buried the fossil valley (the fossil valley sediment) was classified roughly into the following layers:

1) Deposit of the present flood plain
This was the surface layer that was probably deposited by the floods of the present river. This layer, which was 0.3 to 0.7 m thick in general, mainly consisted of clay, sand and organic soil. In some places, its lower layer, the "upper stratum of the fossil valley", was exposed on the ground surface.

2) Upper stratum of the fossil valley
This was clayey or silty sediment extending just under the "deposit of the present flood plain" to 4 to 5.5 m below the ground surface. This stratum contained sandy layers in the form of a 0.5- to 1-m-thick belt or lens. During the construction of the subsurface dam, there was a great quantity of water springing from these sandy layers, which prevented excavation work for a while.

3) Lower stratum of the fossil valley
This stratum, which extended from 4 to 5.5 m below the ground surface down to the bottom of the fossil valley (except some parts), consisted of layers of sand, granules, silt and lignite. The boundaries of these layers were relatively clear. Each layer had an interfinger or massive structure. The sand layers had partial cross-lamination. Most of the granules and the coarse sand seemed to have their origin in the oolitic concretions of the lateritic crust.

There were penetrations in the form of an interfinger of the silty or sandy layers, which were classified as the "upper stratum", into some parts of this "lower stratum". The distinction between the "upper stratum" and the "lower stratum" was thus not very strict.

4) Basal stratum of the fossil valley sediment

At some parts between the "lower stratum" and the basement rock, a stratum of hard silt rock interposed. Its clear unconformity with the "lower stratum", and its advanced compaction and cementation compared with the other fossil valley sediment that had an unconsolidated or semi-consolidated state showed that this stratum of hard silt rock was formed much earlier than the "lower stratum".

In the lower part of this "basal stratum", a piece of angular gravel was observed. It is probably a remnant of the fluvial deposits dating back to when the fossil valley was formed by active erosion by the old river.

5) Basement rock

The bottom and the side slopes of the fossil valley consisted of basement rock (old age rock) that had the appearance of contaminated rock composed of granite, diorite, amphibolite and slightly metamorphosed sedimentary rock. The basement rock of the right bank of the valley was covered with a hard, lateritic crust about 3 m thick.

On the basement rock of the bottom of the fossil valley, a fault (argillized zone 0.5 m wide) with a strike slightly oblique to the direction in which the fossil valley extension was observed. On the basement rock around this fault, fractured or heavily argillized zones were also observed.

(3) Difference in hydraulic characteristics among the constituent layers of the fossil valley

The permeability coefficients of the sand layers in the "upper stratum" and in the "lower stratum" of the fossil valley sediment were estimated to be 10^{-2} to 10^{-4}cm/sec. On the other hand, those of the silt, the cemented sand and the lignite layers fell to 10^{-6} to 10^{-7}cm/sec.

The excavation for the construction of the subsurface dam encountered perched water (groundwater that accumulates in the lens shape above the "main" groundwater), from which a great quantity of water sprang. The presence of this perched water can be explained by a significant difference, as described above, in the permeability coefficients among the constituent layers of the fossil valley.

At the part where the boundary between the "upper stratum" (silty layers) and the "lower stratum" (sandy layers) was clear, there was a space 0.5 to 3 cm wide between both strata. On the roof of this space, there was thick "water grime", which indicated that this space had been a groundwater channel for a long period. (See Fig. 5.1)

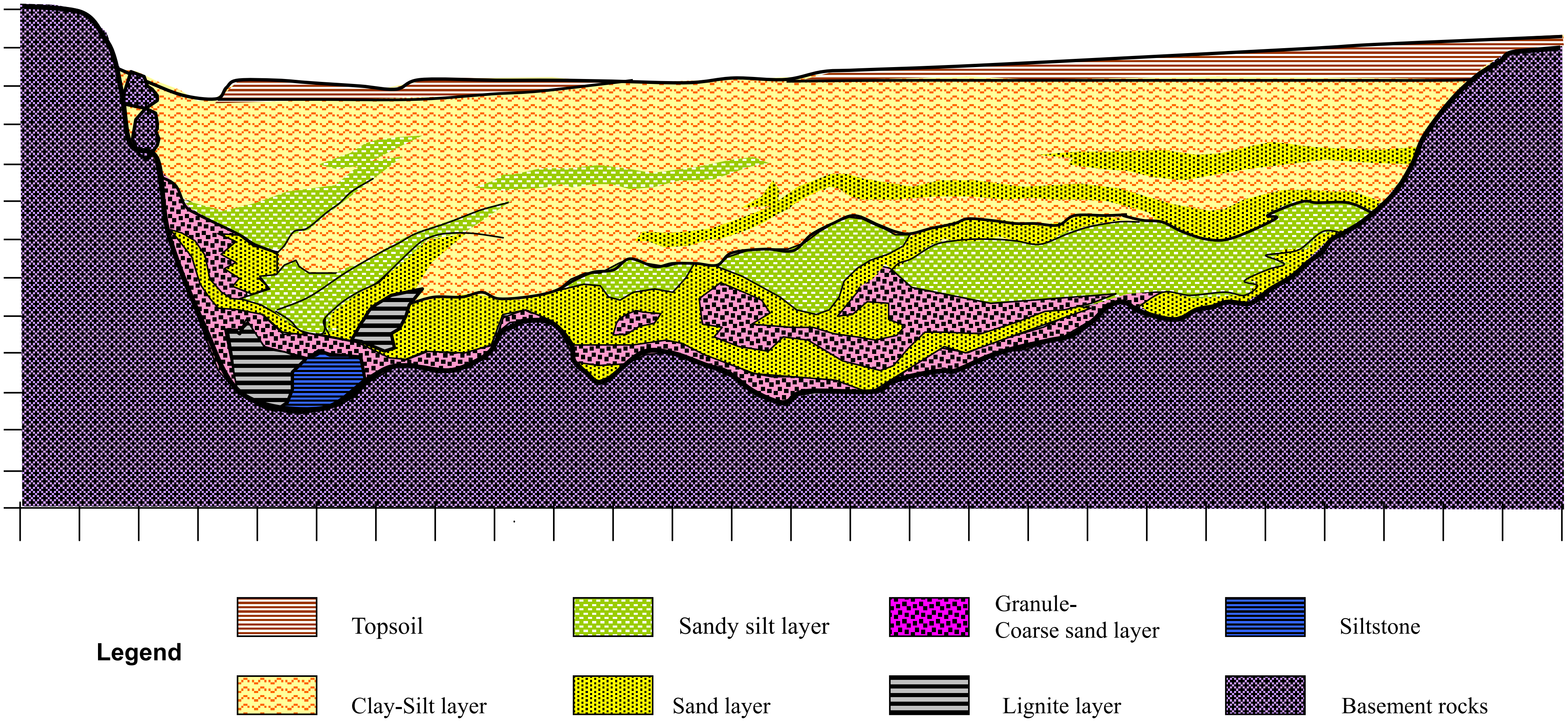


Fig.5.1: Geological cross-section of the "fossil valley" at the subsurface dam site (upstream excavation profile)

Note: The vertical scale of the profile is different from the horizontal scale.

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.

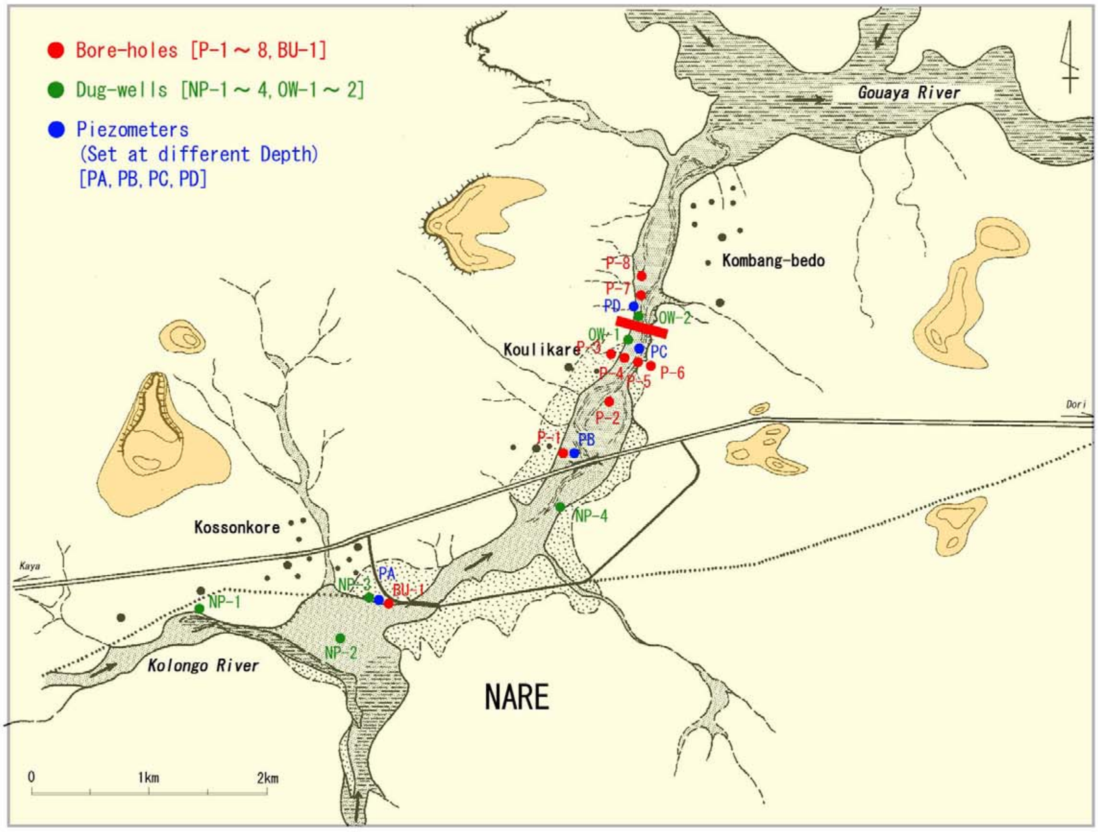


Fig. 6.1: Schematic diagram of the distribution of facilities for groundwater observation

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

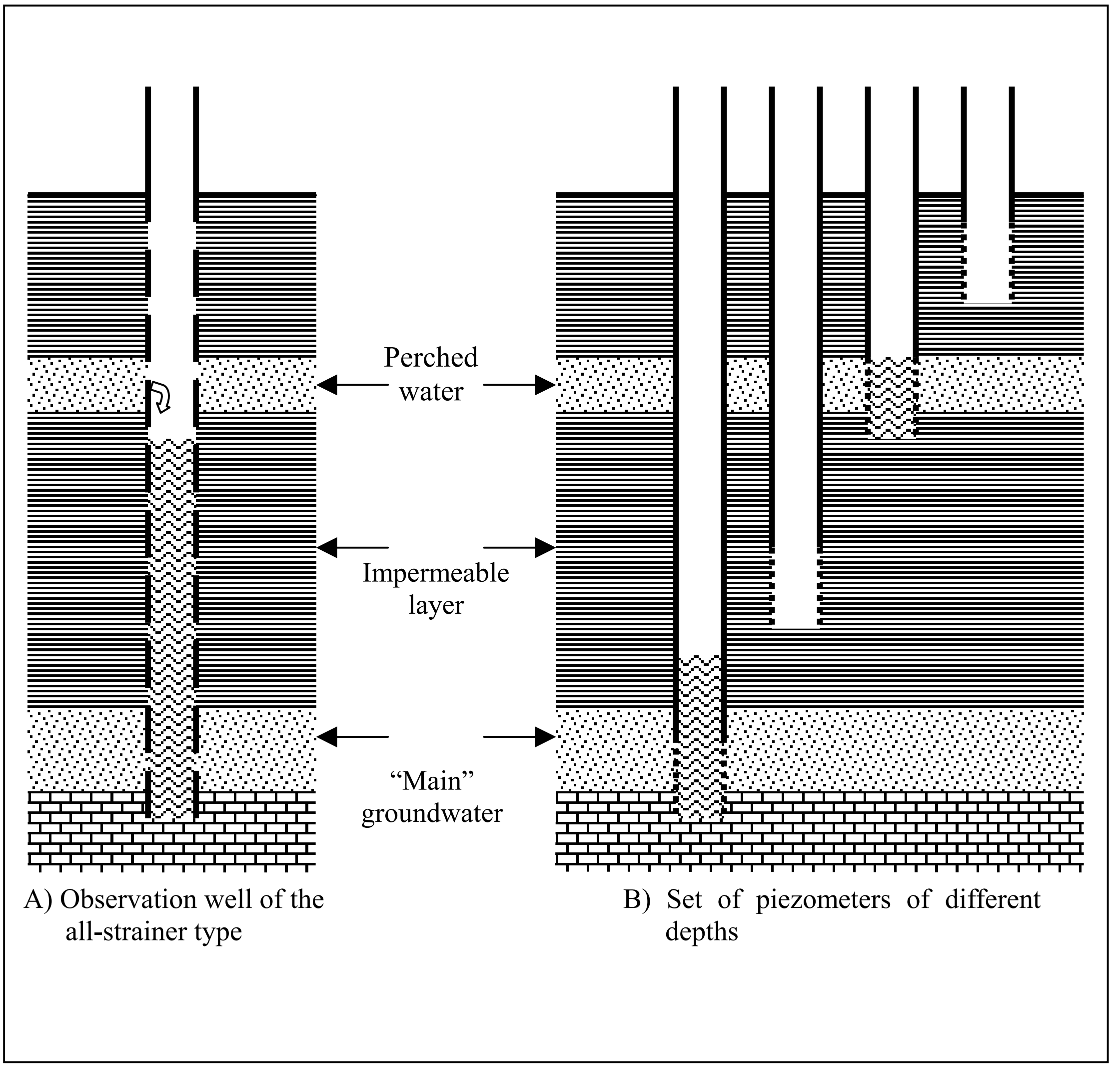


Fig. 6.2: Structure of two types of groundwater observation well

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.

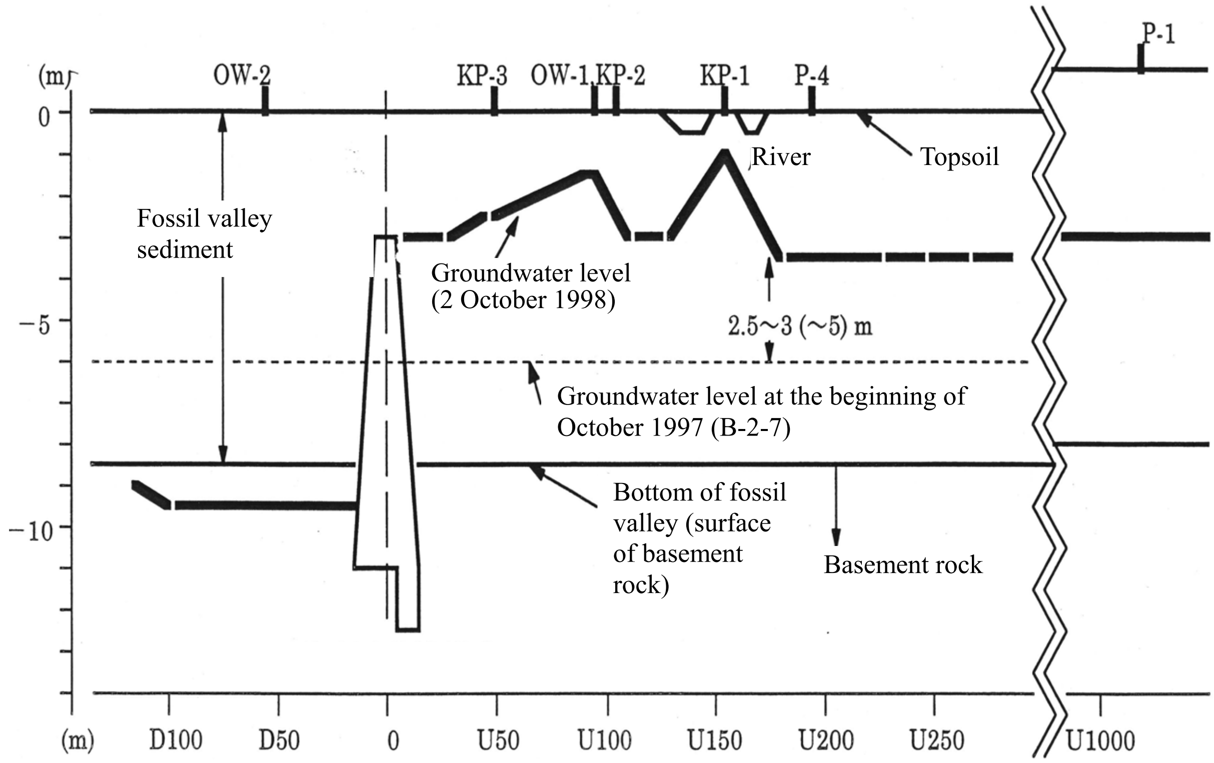
1) Every year, the reserved water level rose in the rainy season and fell by 2.5 to 4.5m by May and June, i.e., between the end of the dry season and the beginning of the rainy season.

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.

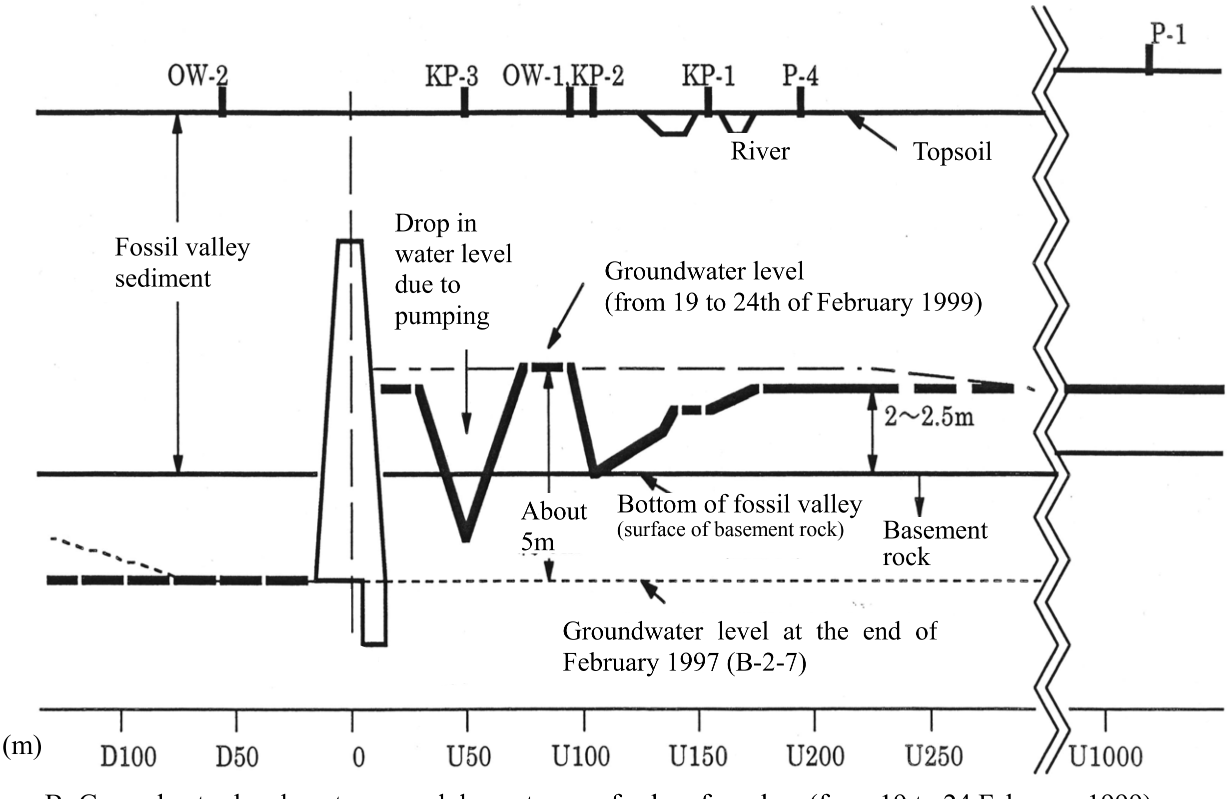
3) The reserved water level during the rainy season of 2000 was very low compared with that of the previous years, and the lowest level between the end of the dry season and the beginning of the rainy season fell in 2001. This can be attributed to the exceptional drought in 2000 around Nare Village. 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

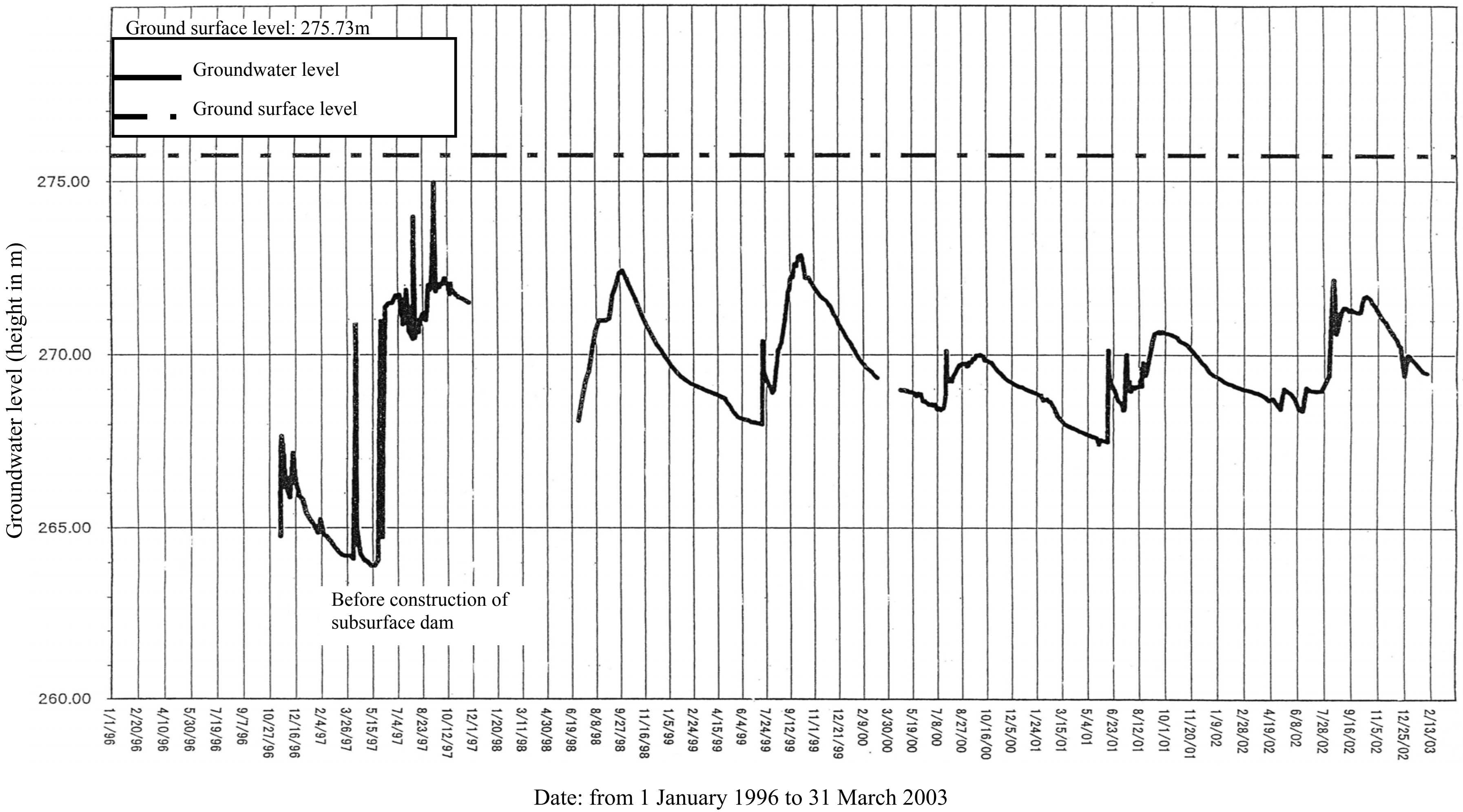
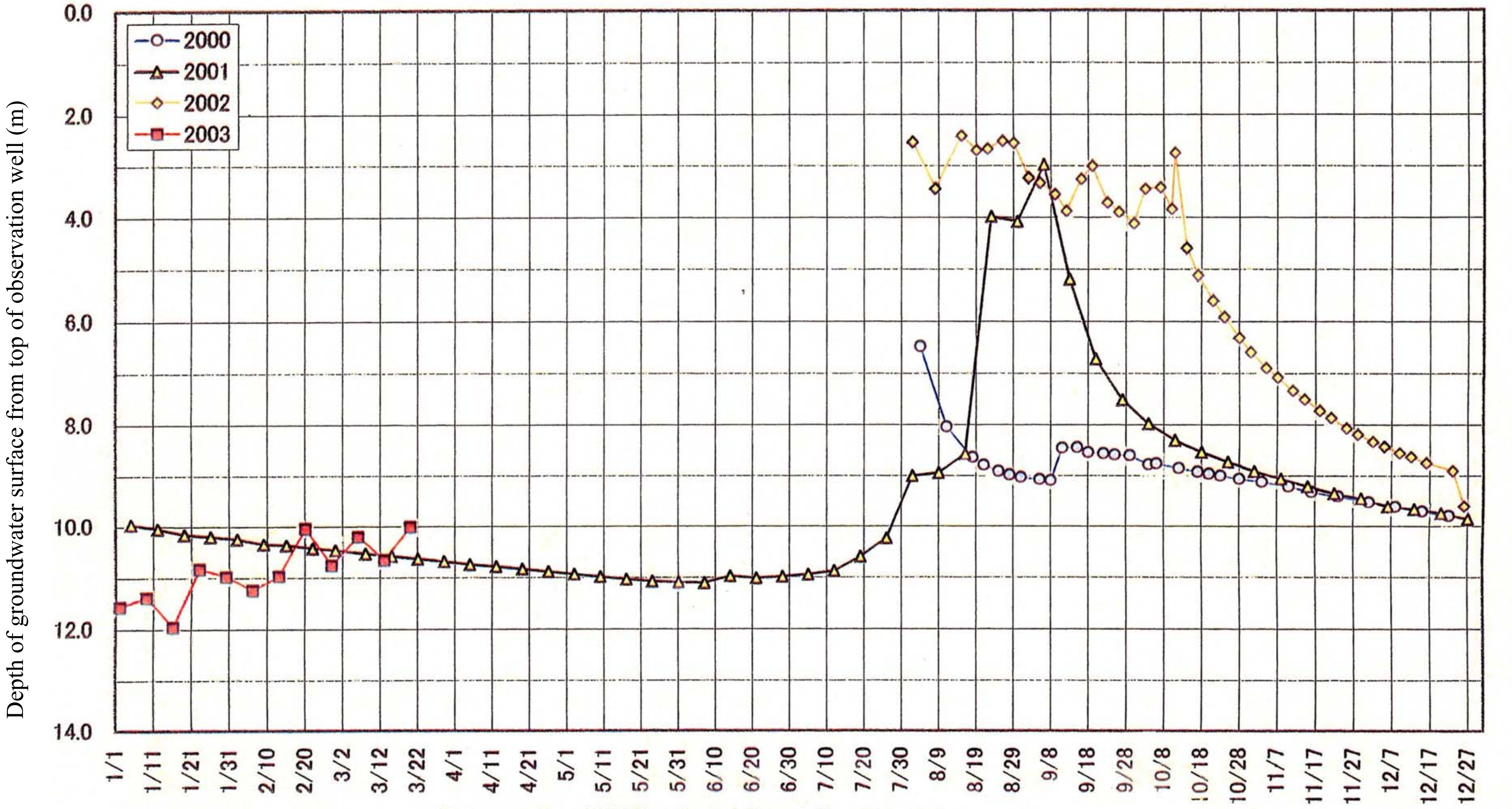


Fig. 6.4: Results of continuous observation of reserved groundwater level by the subsurface dam (at observation well P-4)



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".

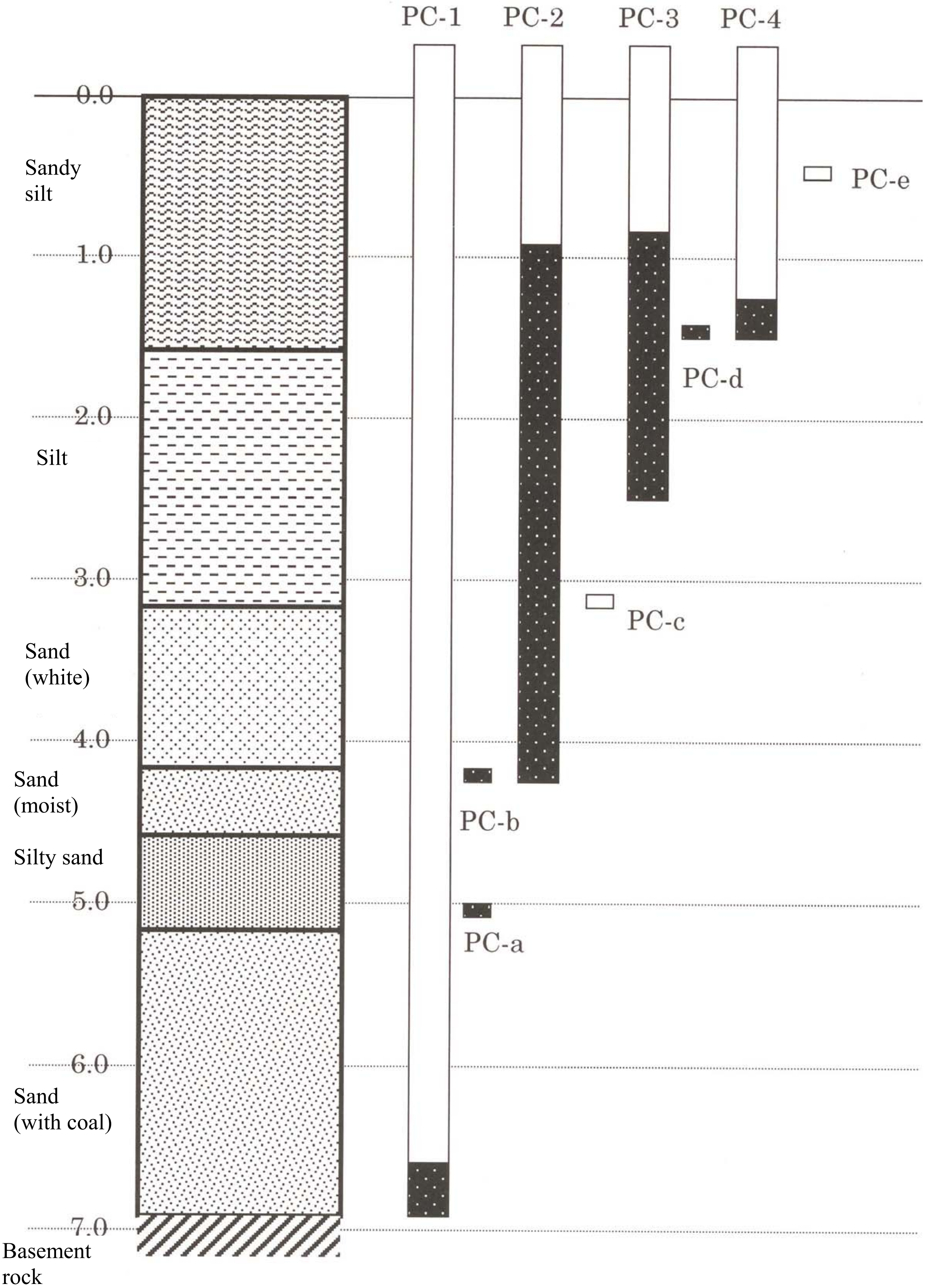


Fig. 6.6: Results of observation using "set of piezometers of different depths " (at observation well PC) (20 July 2000)

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.

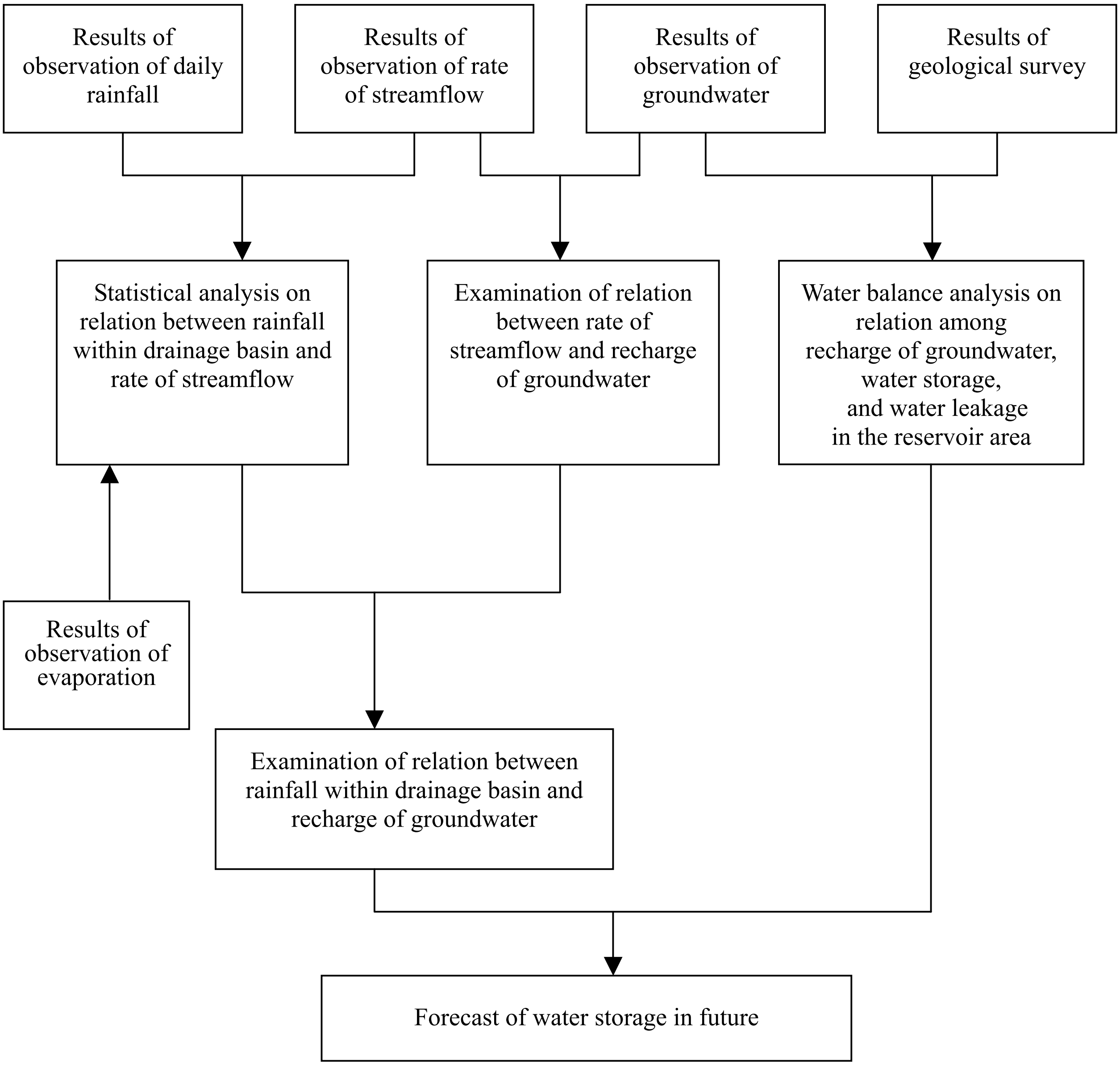


Fig.6.7: Flowchart of analysis of the water-storage mechanism

(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 ＝0.022 X ＋29,000**	Correlation coefficient = 0.615
From July to October:	**Y ＝0.057 X ＋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:

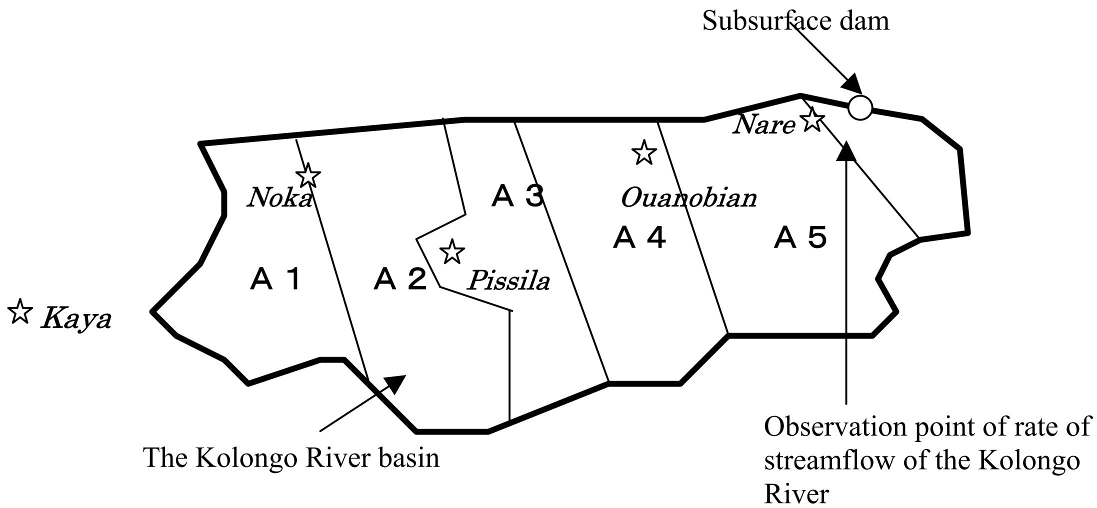


Fig.6.8: Relation between the daily rate of streamflow and rainfall within the drainage basin at observation points in Nare Village on the Kolongo River

7. Other studies

In addition to the surveys and the observations described above for the construction of the subsurface dam and the evaluation of its effectiveness for water storage, the following studies were undertaken in this project.

(1) Experimental installation of water-supply facilities operated by solar energy
Water-supply facilities operated by solar energy were set up as follows to study the effective use of the reserved water by the subsurface dam (see Photographs at the end of this chapter):

- Water-pumping wells: 3 dug wells installed in the reservoir area of the subsurface dam (with about a 20-m depth)
- A solar power station: 3 solar panels generating 1.76 kwp of electricity
- Water supply facilities: A water tower whose volume is10 m^3, a water-supply station for domestic use (communal water taps), a water trough for livestock animals, and irrigation facilities for agricultural pilot studies

Namely, water was pumped up to the water tower from the 3 pumping wells by underwater motors operated by solar energy, and was distributed to the water-supply facilities installed in Kombangbedo Village for domestic and other uses.

Water provided by these facilities reached more than 30 m^3/day at maximum just after the start of the water supply. Thereafter, it fell to about 2,700 m^3 in 2002, i.e., 7.4 m^3/day on average, after the installation of hand pumps in the village and the voluntary restriction of water supply for livestock animals by the villagers themselves.

(2) Agricultural pilot studies
To study the effective use of groundwater for agriculture, a pilot farm was set up, and agricultural pilot studies were carried out there with the water provided by the water-supply facilities operated by solar energy mentioned above. The cultivation of cereals (millet and sorghum) and vegetables (tomato, onion, etc.) by drip irrigation, negative pressure irrigation and manual irrigation were tested, changing the water volume conditions.

The results of these studies showed that irrigation with appropriate water supply ensured harvest even in "a year of extraordinary drought". However, to use the reserved water by the subsurface dam for agriculture operationally, it is necessary to develop methods of irrigating large areas of land effectively and economically.

(3) Installation of a small-scale surface dam with water gates
To facilitate the recharge of groundwater, and support the development of agriculture and inland water fishing, a “small-scale surface dam with water gates” was installed on the Kolongo River 1.5 km upstream of the subsurface dam (see Photograph at the end of this chapter).

This “small-scale surface dam with water gates” was set up using the existing embankment of the main road as a dam body, attached with 23 water gates. The length of the dam body was 33 m, and the maximum water level of the reservoir was 1.2 m.

The gates were opened and closed by the inhabitants who grew rice on the flood plain. This surface dam increased largely the field area for rice crops on the flood plain, and the fishing catch from the reservoir of this surface dam also appeared to be increasing.

(4) Vegetation research for environmental impact assessment
To assess the impact of the change in groundwater state caused by the subsurface dam on the environment, the following vegetation research, mainly on trees, was carried out:

1) Follow-up research of vegetation change around the reservoir area of the subsurface dam: This research was carried out between 1998 and 1999. In the reservoir area of the subsurface dam and its vicinity, whose total area was about15 km^2, 29 observation points at about 500-m intervals were selected, and species, height and diameter of the trees, etc. were observed. Furthermore, vegetation change thereafter at the same points was also researched between 2001 and 2002.

2) Life historical research on tree growth upstream and downstream of the subsurface dam: This research was carried out between November 2000 and December 2002 in research zone 50 to 100 m upstream and downstream of the subsurface dam, to compare the difference of the tree growth between the upstream side and the downstream side.

The target species of this research were *Acacia seyal*, *Mitragyna inermis* and *Piliostigma reticulatum*. In this life historical research, the vigorousness and shape of the trees, the state of the leaves (budding and defoliating seasons, color and volume of leaves, etc.), the state of the flowers (flowering season, volume of flowers), and the state of the fruit (fructification season, volume of fruit, etc.) were mainly observed. The research interval was once or twice a month.

In addition to this research, an inventory of the species was made before water storage by the subsurface dam, and examination for quantitative methods of environmental impact assessment was carried out.

The follow-up research mentioned above in 1) did not show any vegetation change in the reservoir area and its vicinity, except for the obviously artificial vegetation. On the other hand, the life historical research mentioned above in 2) showed that the defoliation season clearly tended to be earlier in the area downstream area than in the area upstream of the dam, which suggests a difference in the soil moisture content between the upstream side and the downstream side. However, dead trees were not found upstream or downstream.

Thus, the difference in the vegetation state between the upstream side and the downstream side of the subsurface dam was only “environmental change” observed since the construction of the subsurface dam until the end of 2002. This difference might also be attributed to the difference in the presence of surface water, and it was not clear whether the difference was affected by the construction of the subsurface dam or not.

(5) Research on awareness of this project by inhabitants
In January and February 2002, awareness of this project by inhabitants was researched in the form of an interview in Nare and nearby villages.

The results show that the inhabitants had a positive feeling toward this project in general.

It should be noted that the following facilities were set up during the model project but independently of it. Some staffs of the model project participated in the running of some of these facilities:

- 3 mill stations, by "Grant Assistance for Grassroots Projects" from Japan
- 4 hand pumps, by Grant Aid from JICA (Japan International Cooperation Agency)
- 1 vegetable garden equipped with 4 large-diameter wells for the women of Nare Village, by the government of Burkina Faso
- 4 vegetable gardens, by a Japanese NGO (GEO-Action)

Photo 7.1: Solar power station for pumping

Photo 7.2: Pumping well installed in the reservoir area of the subsurface dam
(The well is surrounded by concrete walls for protection from river floods.)

Photo 7.3: Water-supply station for domestic use, installed in Kombangbedo Village

Photo 7.4: Pilot farm in this project
(The reserved water by the subsurface dam, pumped by solar power station, was used for irrigation.)

Photo 7.5: Small-scale surface dam with water gates, installed in this project

8. Recommendations for future subsurface dam projects

The above-described results of the pilot study of the subsurface dam as the “Model Project to Combat Desertification” showed that the "subsurface dam technology" developed in Japan were applicable to West Africa, a region affected by desertification.

However, to construct operational subsurface dams adapted to the physical and social conditions of the region, sufficient attention should be paid to the following.

8-1 Selection of subsurface dam sites

(1) Evaluation of "fossil valley"
In this project, the subsurface dam was built using an existing fossil valley. Although water leakage from reservoir area occurred, it was confirmed that the construction of a subsurface dam using a fossil valley was possible.

It is said that there are many fossil valleys in the Niger River basin, and there may be many possible sites for the construction of subsurface dams.

It should also be noted that the fossil valley is often accompanied by shallow groundwater, and in general, by a wide area of flat lowland. Therefore, fossil valleys seem places with high potential for the development of irrigation or livestock farming. It is desirable to examine the distribution of fossil valleys and their characteristics not only for the construction of subsurface dams, but also from this viewpoint.

(2) Geological structures other than fossil valleys
Although the surveys for the subsurface dam site in this project were carried out targeting “ring-shaped landforms” and “bottleneck-shaped landforms” as well, proper geological structures from these landforms except “fossil valleys” were not found. However, more detailed surveys would make it possible to find proper dam sites from geological structures other than “fossil valleys”, even if these surveys require enormous effort.

(3) Difficulty in estimating exploitable groundwater
In selecting the subsurface dam site, it is necessary to estimate the volume of groundwater to be stored. However, estimating the "water to be stored", which is relatively easy in case of a surface dam, encounters the following difficulties in case of a subsurface dam:

1) Because the water storage layer of a subsurface dam is formed under ground, it is difficult to precisely determine its form and volume.

2) The water storage capacity of a subsurface dam depends on the effective porosity of the geological strata. Determining the effective porosity of all parts of the water storage layer requires a significant survey effort.

3) It is difficult to precisely estimate the recharge of groundwater into the water storage layer.

4) It is difficult to detect water leakage points from the water storage layer, and to forecast the volume of water leakage.

In future subsurface dam projects, it is advisable to carry out more detailed surveys to estimate more precisely the volume of water to be stored. Nevertheless, even with such an estimate, it is impossible to completely avoid fairly large error. This should be taken into account in selecting subsurface dam sites and in making plans for using the reserved water.

(4) Selection of dam site from a socio-economic viewpoint
In this project, taking into account its experimental character, priority was given to the hydrogeological conditions in selecting the subsurface dam site. In future subsurface dam projects for practical purposes, socio-economic factors should be taken into account as well.

In general, using the reserved water by the subsurface dam requires "water-pumping facilities". If the subsurface dam is located far from where the reserved water is used, large "water-supply facilities" are also required. In some cases, the cost of the installation of these facilities may be higher than that of the construction of the subsurface dam.

Therefore, in selecting the subsurface dam site, the following factors should be taken into account for better cost-effectiveness:
- Population that will use the reserved water
- Possibility of developing irrigation or livestock farming using the reserved water

In addition, note that if polluted water enters the reservoir area of a subsurface dam, it takes an enormous amount of time to restore the water quality due to slow water circulation. Therefore, precautions against water pollution by agricultural chemicals, for example, should be taken when using the land within the reservoir area.

8-2 Survey methods

(1) Use of aero-photographs
Most of the study area for this project was very flat, so the use of aero-photographs was essential for the field exploration. The use of aero-photographs is effective in general in field exploration in areas with huge peneplains such as in Africa. It is thus desirable to disseminate the technique of using aero-photographs to African engineers engaged in geomorphological and geological studies.

(2) Points to be noted in observing groundwater
It was revealed that there were some perched water bodies in the fossil valley sediment at the subsurface dam site in this project, and the existence of this perched water strongly affected the results of the observation of groundwater level. It is thus necessary to note that it is possible to overestimate seasonal fluctuation in the groundwater level due to the presence of perched water.

In general, perched water may not only be in fossil valley sediment, but also in basement rock.

(3) Importance of hydrological observation (rainfall, rate of streamflow, groundwater level, etc.)
The surveys and the evaluations in this project encountered difficulties due to a lack of existing hydrological data on rainfall, rate of streamflow, groundwater level, etc.

As rainfall sometimes shows an extreme difference even between relatively close points, it is advisable to arrange rainfall stations more densely in areas where there is a shortage of water resources as in the Sahel. In addition, as variation in river water is closely related to the exploitation of river water and groundwater, it is preferable to measure the rate of streamflow as at many points as possible, even in the same river system. As for the groundwater level, although the observation data collected during the excavation of deep wells were relatively well preserved, the data of the groundwater level in shallow wells and the data of seasonal and interannual fluctuation in the groundwater level were limited. These data are necessary for any exploitation of groundwater resources. The establishment of systems for such observation and data-keeping is thus desirable.

(4) Surveys in the reservoir area

As described in Section 8-1-(3), form, volume, hydraulic characteristics and possibility of water leakage of the reservoir layer of the subsurface dams are not easy to determine. Surveys to determine these parameters for the construction of a subsurface dam are thus important.

8-3 Methods of construction of a subsurface dam

(1) Disadvantages of a "subsurface earth dam"

The method of construction adopted for this project was to install an "earth dam" (earth dike) under ground. This method poses the problem of "water springing" during construction. In this project, there was little “water springing” from the excavation face of the fossil valley sediment and special measures were not necessary. However, when there is a lot of shallow groundwater and stopping “water springing” is difficult, it sometimes becomes impossible to continue construction.

It should be noted that a subsurface dam to be constructed very deep under ground requires a great quantity of excavation and backfilling, with corresponding costs. The risk of water springing also increases.

(2) Material of the dam body

In this project, the dam body was built with materials extracted from a place away from the dam site. However, surplus soil produced by excavation at the dam site proved usable as the dam material later on.

The reuse of the surplus soil produced by the construction of a “subsurface earth dam” eliminates the need to use material from other places, and thus can reduce the negative impact on the environment. This process should be considered in planning “subsurface earth dam” projects.

(3) Introduction of a "cut-off wall by an underground diaphragm wall”

In this project, the method of constructing the "subsurface earth dam" was selected to use materials available in Burkina Faso. However, the principle of the subsurface dam is the same as that of the "cut-off wall" that is generally used for construction work, and the “cut-off wall” is applicable to the subsurface dam. Especially when, as described above, there is a risk of a large amount of “water springing” during excavation work, or when the dam is to be built very deep under ground, or when shortening the construction period is necessary because work can only be carried out in the dry season, the “cut-off wall method” is better than the “underground earth dam”.

West African countries such as Burkina Faso have recently been advancing the effective use of limited urban space, represented by the construction of high-rise buildings, for example. From now on, this "urban development" will probably extend to the "exploitation of underground space". The “cut-off wall by an underground diaphragm wall (e.g. soil-cement mixing wall method)” was developed as a construction method for such " exploitation of the underground space". Therefore, this method and the necessary machinery will be introduced sooner or later in West Africa.

From this viewpoint, the applicability of the method using a "cut-off wall by underground diaphragm wall" to the construction of a subsurface dam is increasing in West Africa.

8-4 Costs

In this project, the direct costs of the construction of subsurface dam and installation of water-pumping and supply facilities were as follows:

- Construction of the subsurface dam 108,595 thousand yen
- Installation of water-pumping and supply facilities 24,900 thousand yen (part of which is an estimate)

The direct costs of installation of the associated facilities were as follows:

- Facilities for groundwater observation 4,160 thousand yen
- Small-scale surface dam with water gates 16,933 thousand yen
- Pilot farm 2,570 thousand yen

The personnel costs for the Japanese engineers who supervised the entire construction work of the subsurface dam are not included in the costs indicated in this section.

8-5 Management and maintenance system

In this project, when the water-supply facilities started service, the villagers in Kombangbedo Village to which the water was supplied organized a "Committee for the management of the water-supply facilities". This committee collected the water tax, and organized “rotation for cleaning the facilities” as well.

On the other hand, facilities with sophisticated devices such as solar power stations cannot be maintained by the local people alone. It would thus be necessary to set up a system for longer-term management and maintenance with, for example, the assistance of the government of Burkina Faso.

It should be noted however that the solar power station installed in this project was not equipped with "batteries for night storage", which tend to break down.

Thus, ownership by local people and local authorities is essential for the management and maintenance of water resources, including subsurface dams. It is desirable, based on the principle of the participation of local communities and local people, to establish ownership by them from the planning stage of the project.

Acknowledgements

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At the end of the project and this report, we again take this opportunity to express our greatest thanks to all of these organizations and people for their kind support.

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