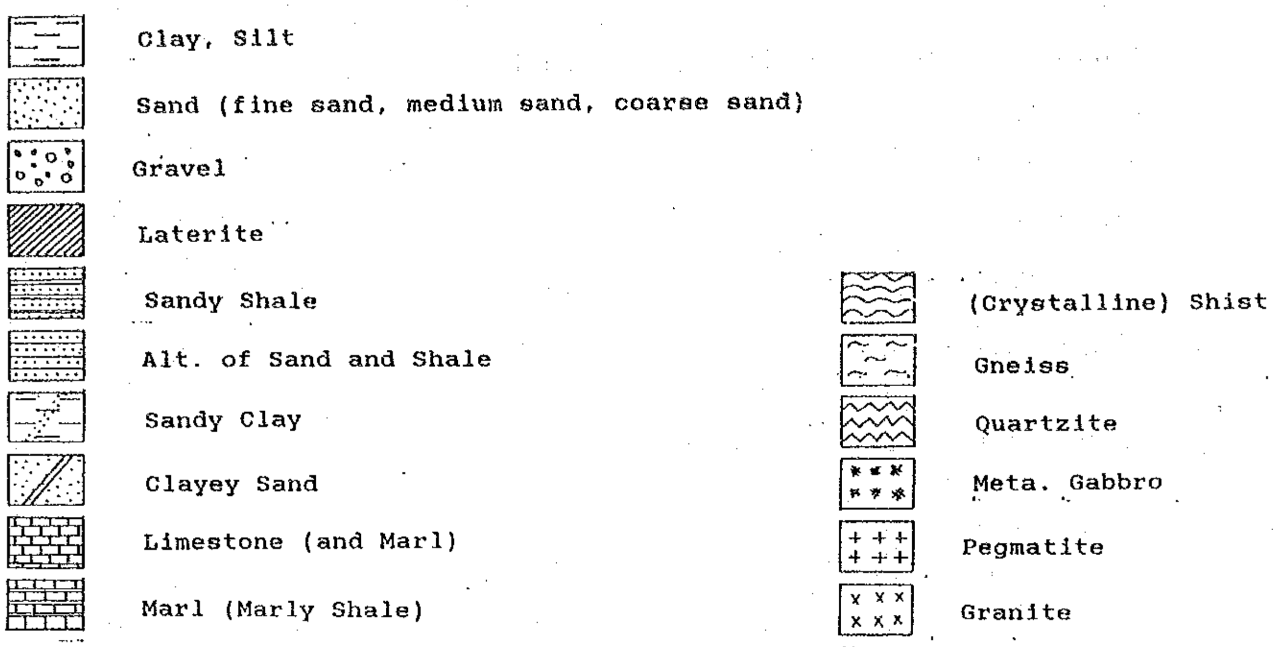
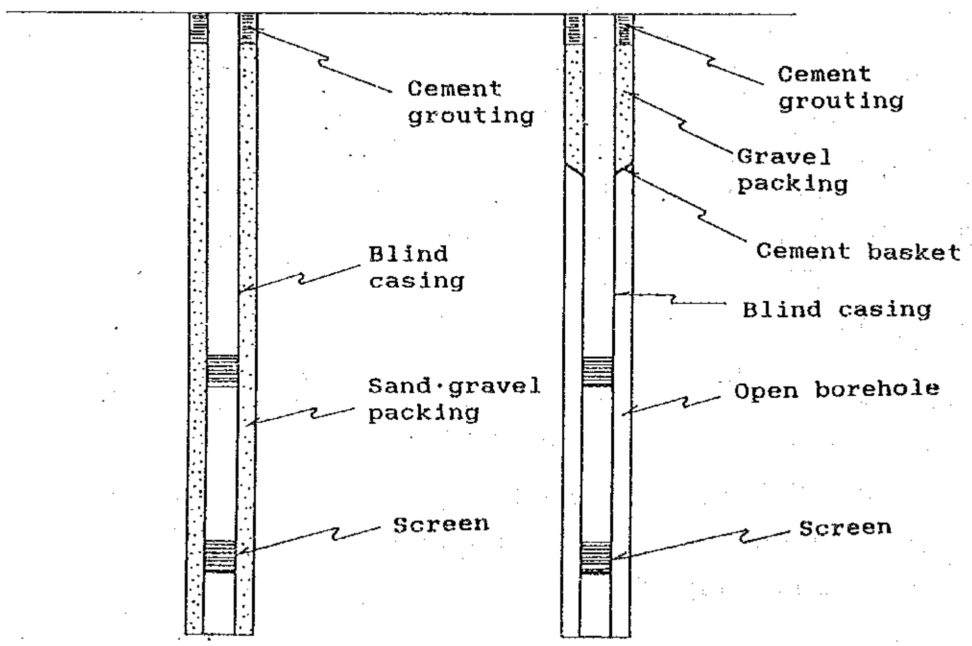
Symbol Materials



Casing Program

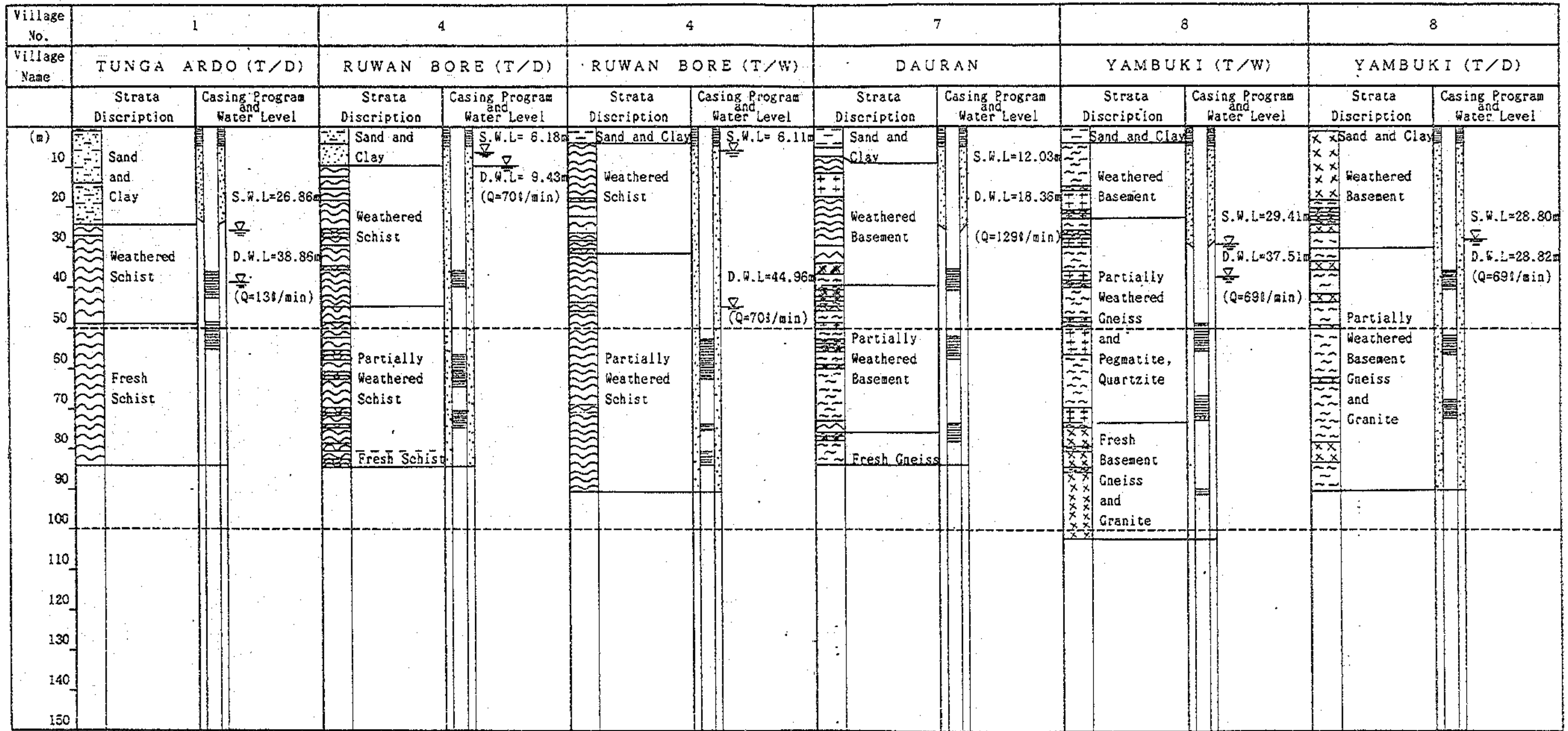


S.W.L : Static Water Level

D.W.L : Dynamic Water Level

Gravel size -> Sedimentary area :ø 1 to 2 mm
Basement Rock area :ø 2 to 3 mm

Fig. 6-19 (1) Results of Drilling



	TUNGA ARDO (T/D)	RUWAN BORE (T/D), RUWAN BORE (T/W)	DAURAN	YAMBUKI (T/W), YAMBUKI (T/D)
Area	Basement	Basement	Basement	Basement
	· Schist 《major water bearing portion》 Weathered Schist	· Schist 《water bearing portion》 Weathered Schist along fractures	· Schist Gneiss · Weathered zone along fractueres · Along Quartzite and Pegmatite vein	· Gneiss,Granite with Pegmatite and Quartzite Weathered Basement(Gneiss,Granite)along fractures
	· No formation stabilizer beneath cement basket(open borehole)	· T/D:Obserevation Well. Distance from Test Well is about 140m-	· Open borehole	· T/W is kept open · Distance betwee T/W and T/D is about 220m

Fig. 6-19 (2) Results of Drilling

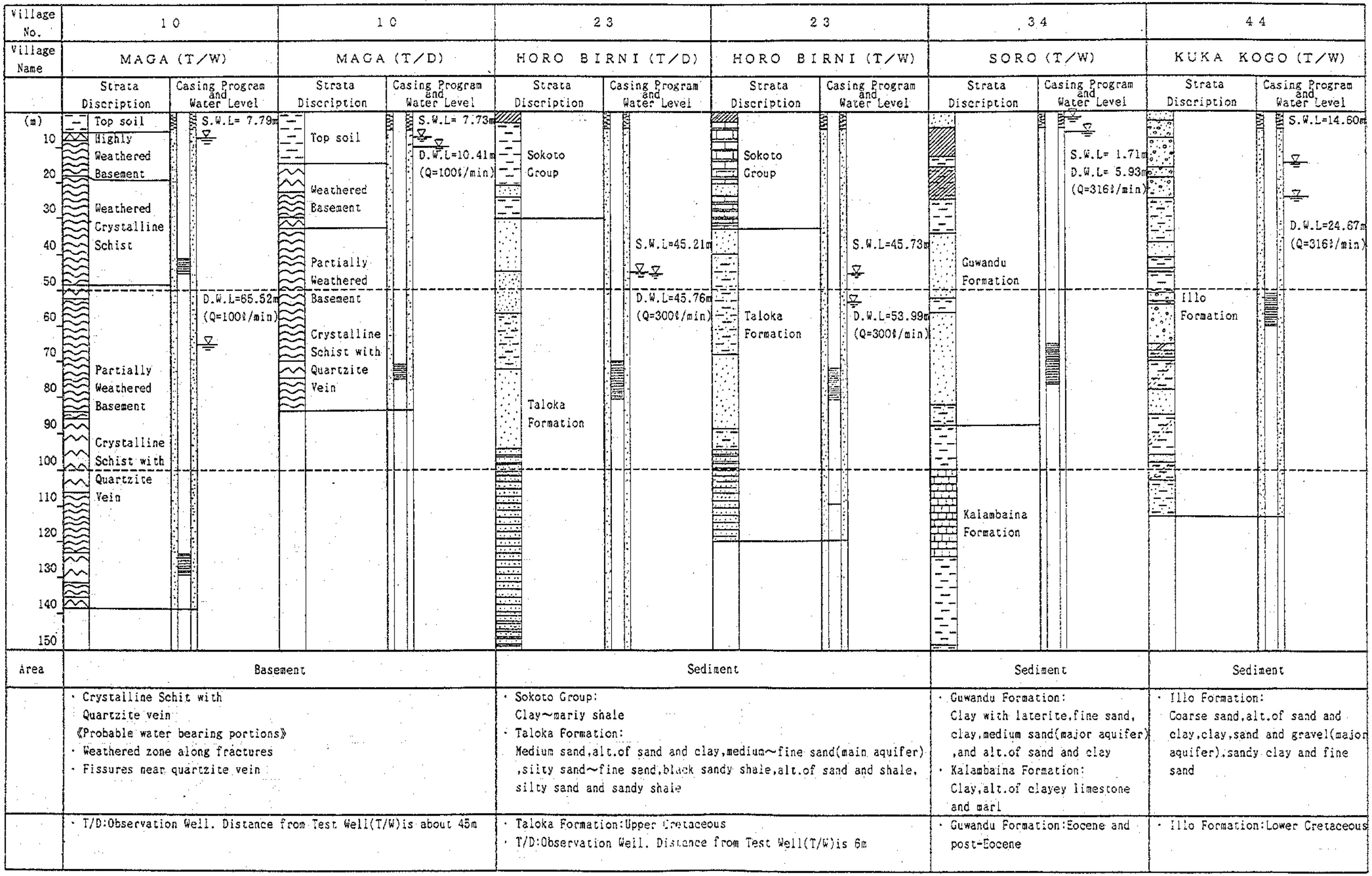


Fig. 6-19 (3) Results of Drilling

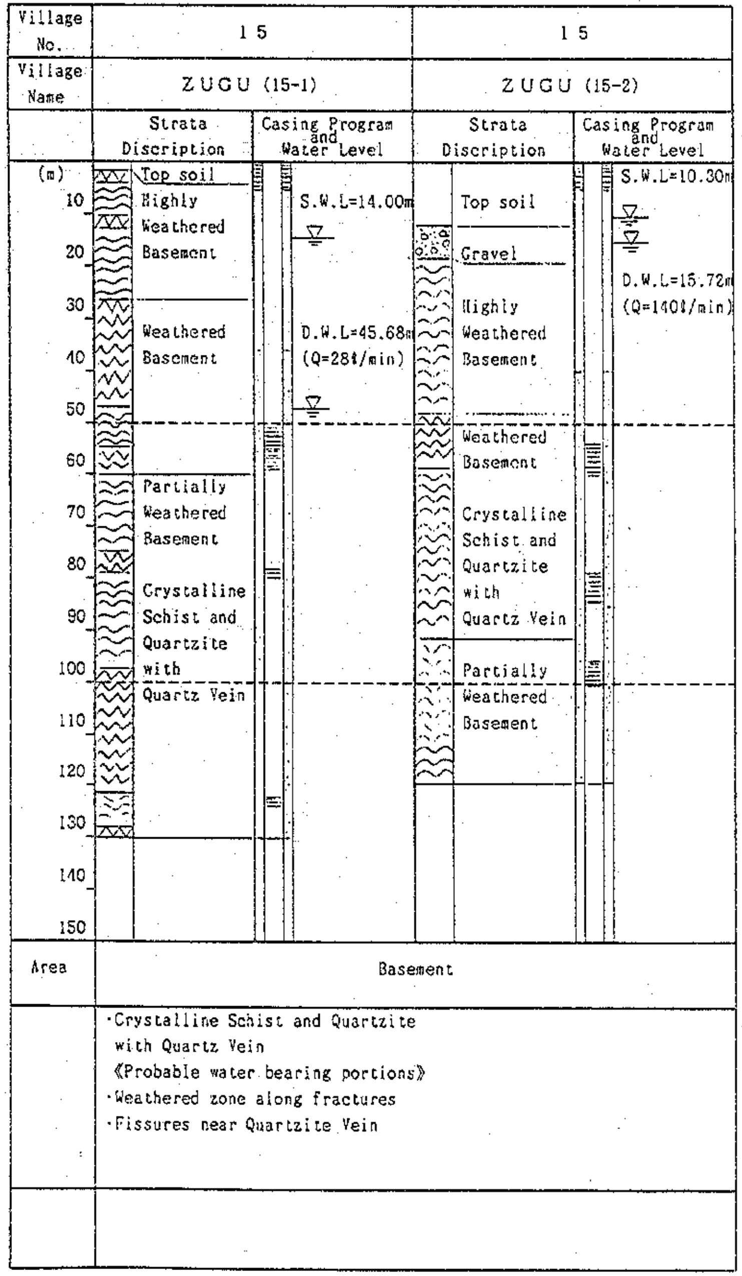


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Tungo Ardo No. 1 (T/D)

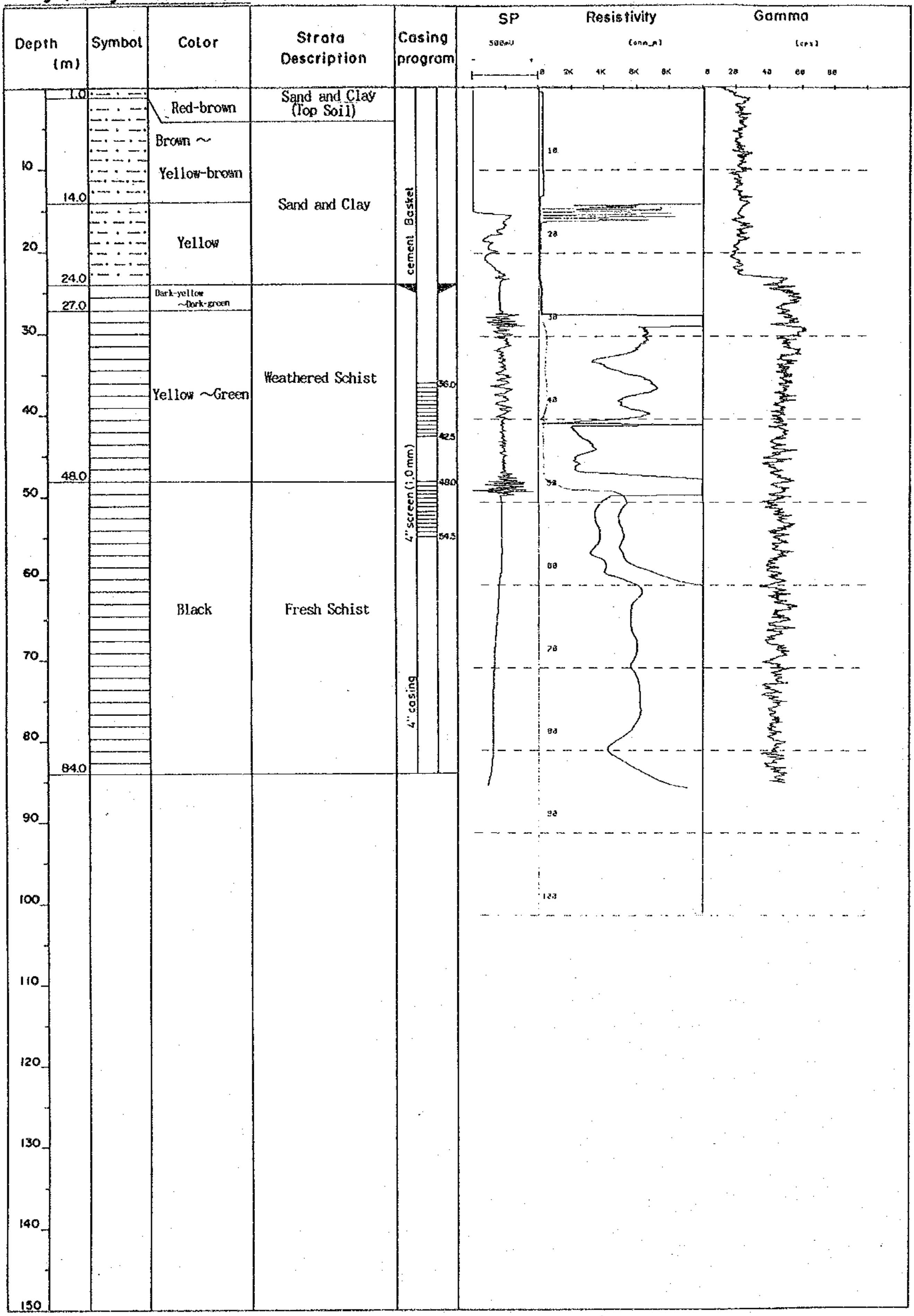


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

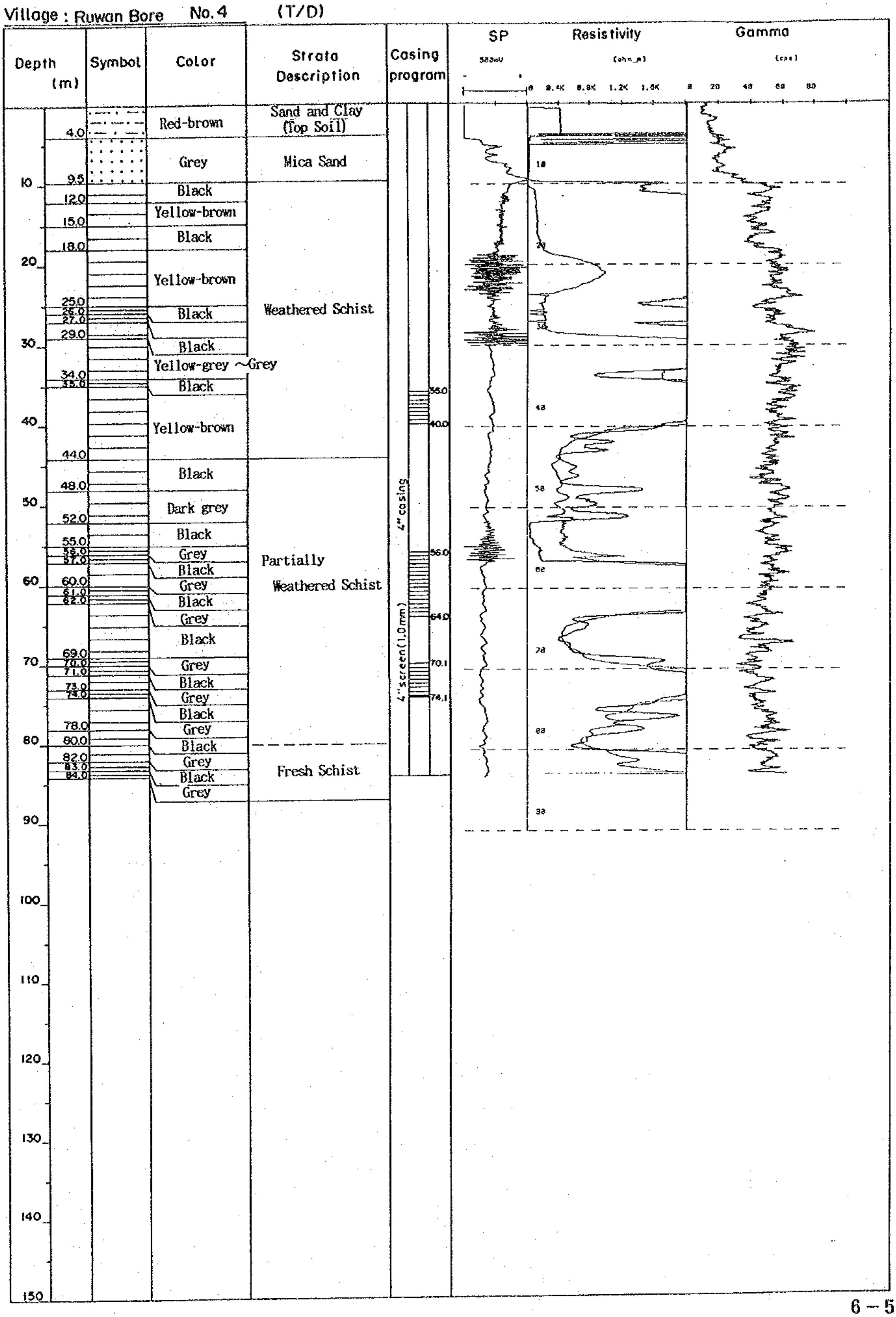


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

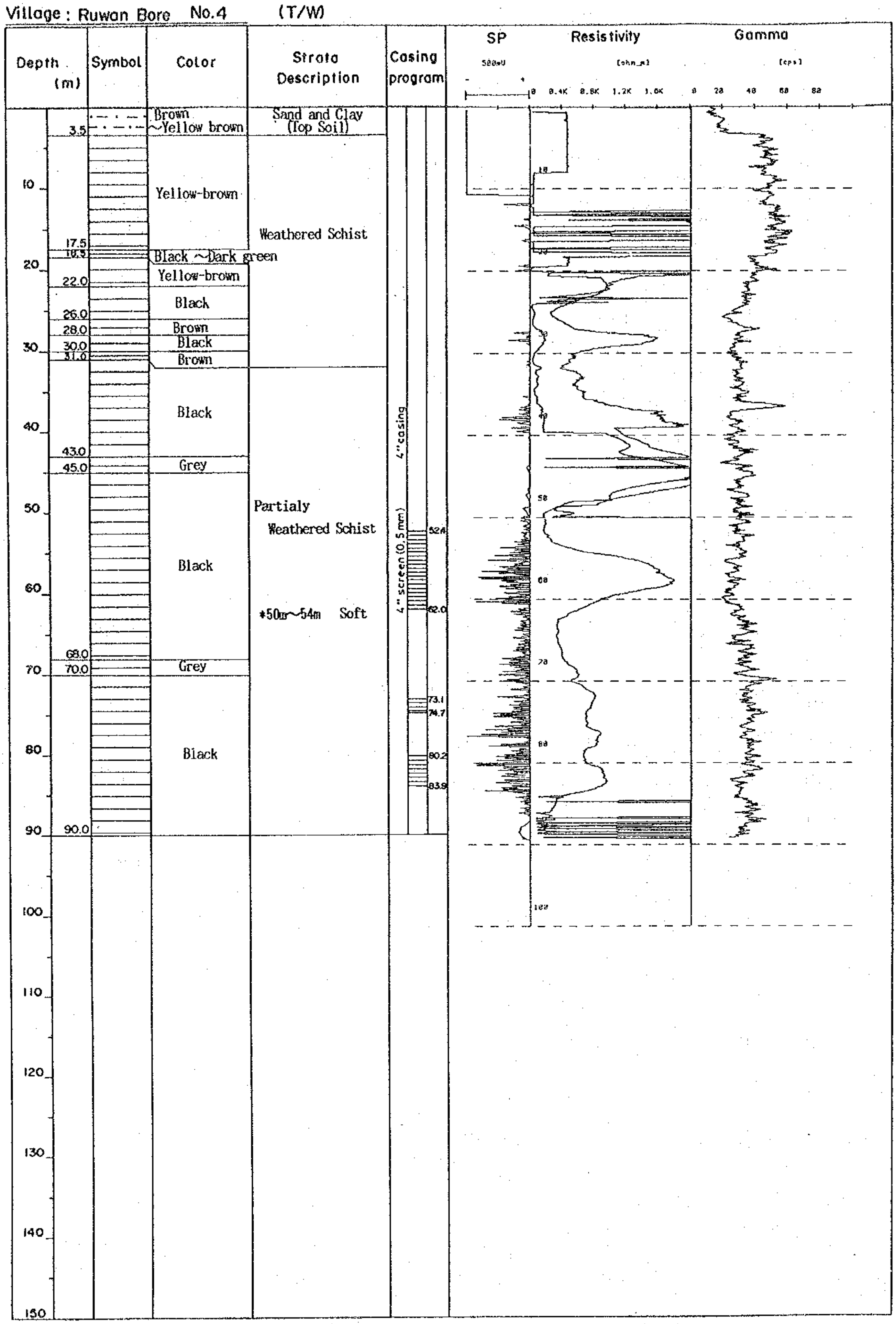


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

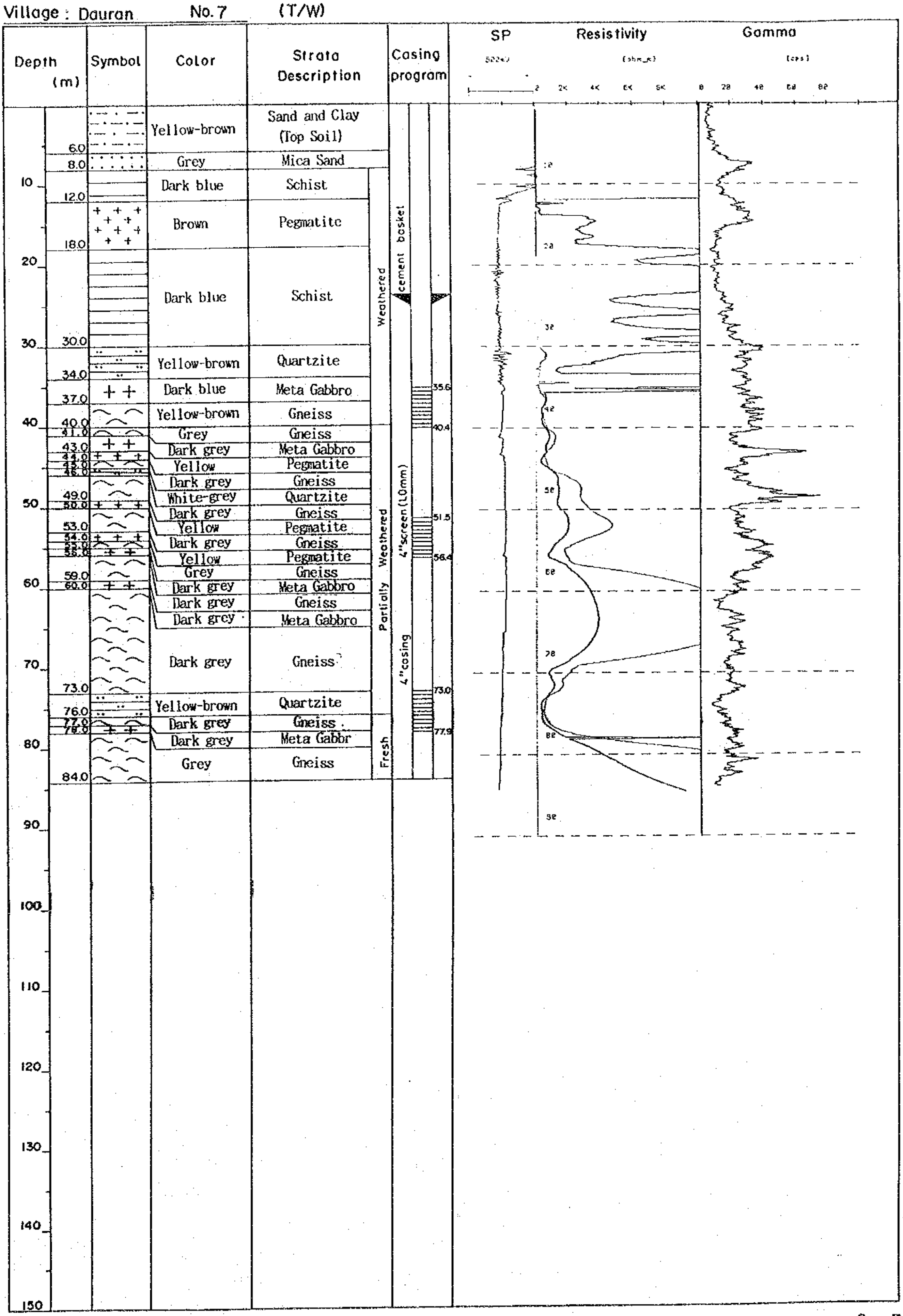


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

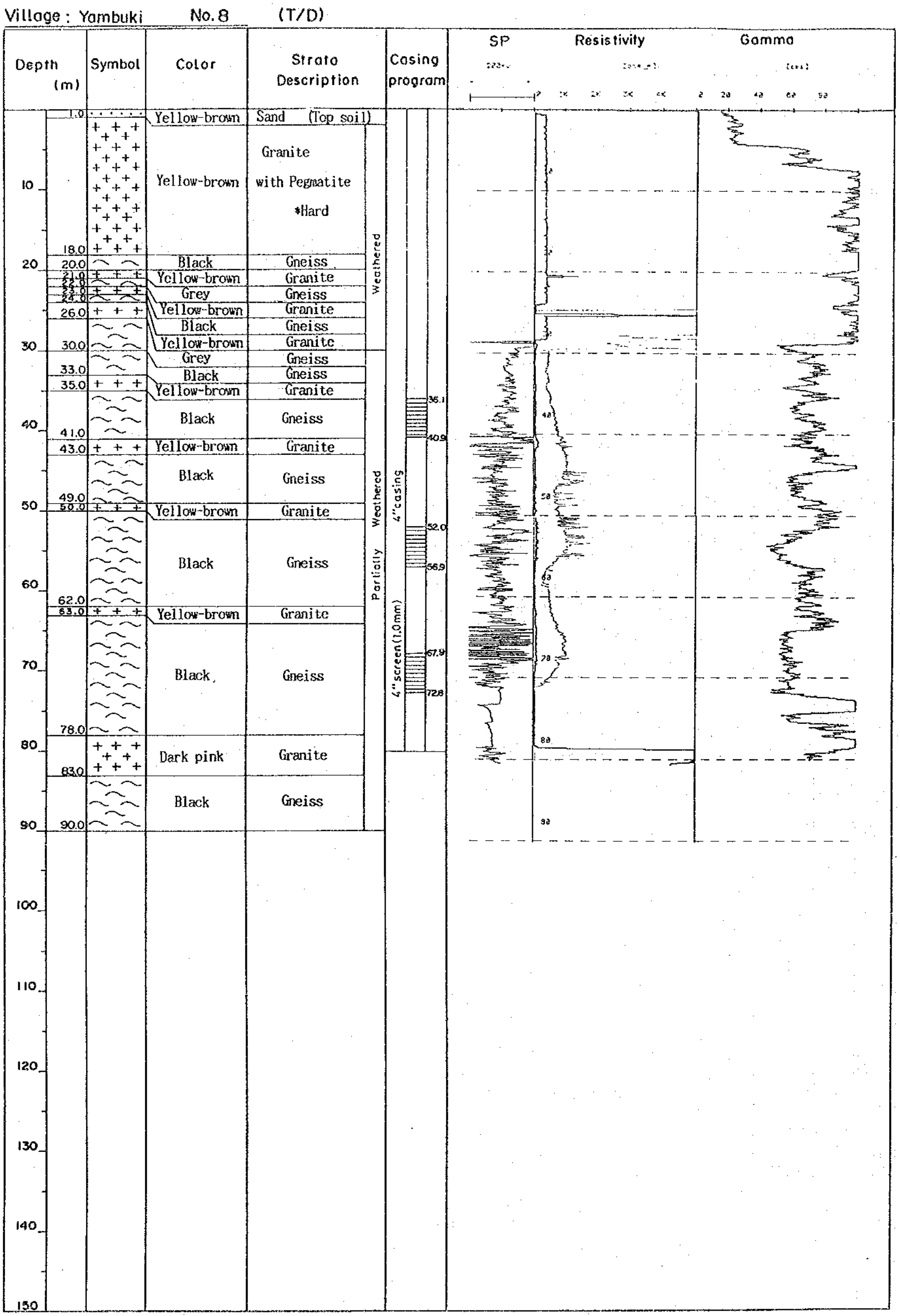


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

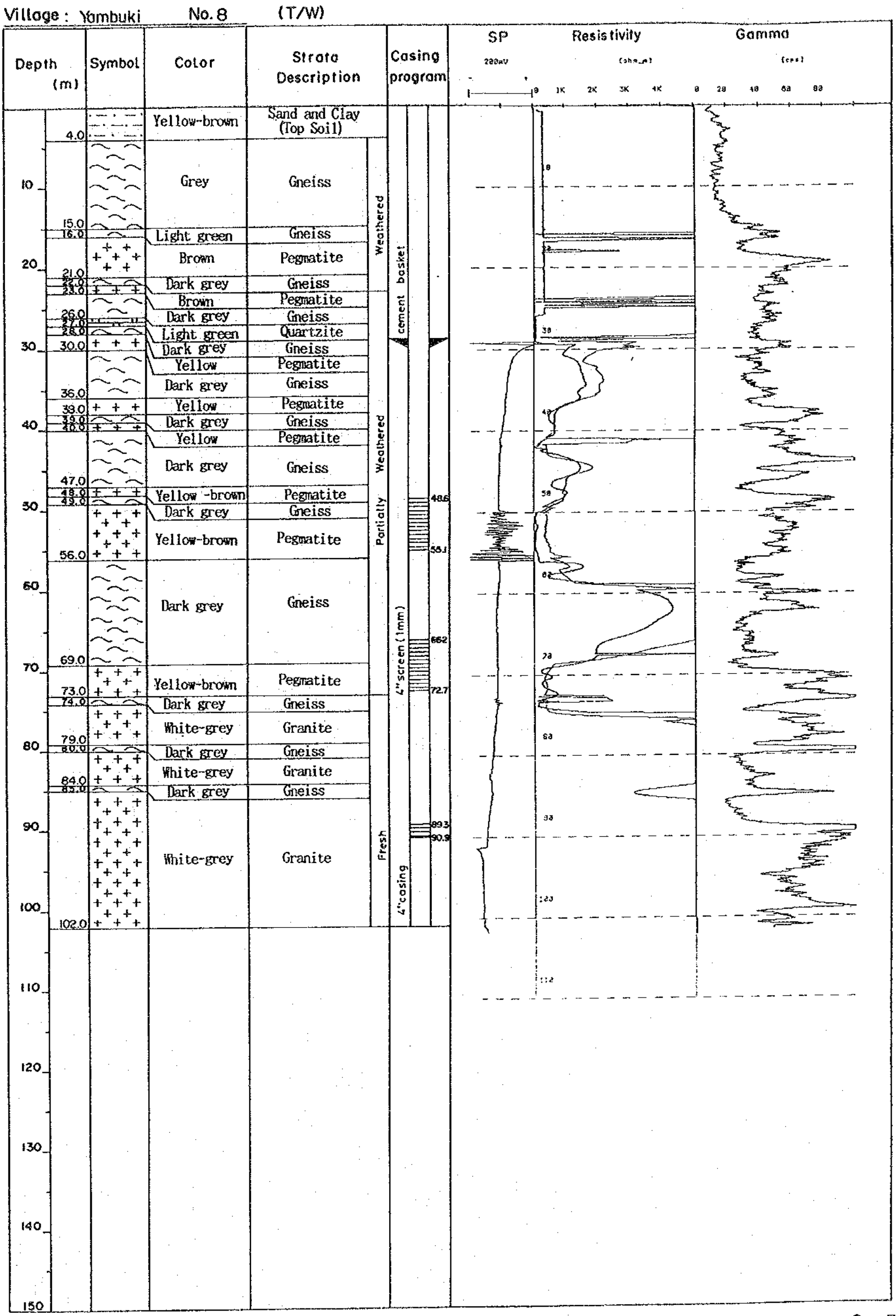


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Maga　　No. 10　　(T/D)

Depth (m)	Color	Strata Description	Casing program
0 – 15.0	Red-brown	Sand and Silt (Top Soil)	4" casing
15.0 – 23.0	Yellow-brown	Weathered Quartzite	4" casing
23.0 – 30.0	Yellow-brown	Weathered Crystalline Schist	4" casing
30.0 – 33.0	Yellow-brown	Weathered Quartzite	4" casing
33.0 – 70.0	Dark green	Partially Weathered Crystalline Schist	4" casing
70.0 – 75.0	Light yellow-brown	Partially Weathered Quartzite	4" screen (71.0 – 75.0)
75.0 – 84.0	Dark green	Partially Weathered Crystalline Schist	4" casing

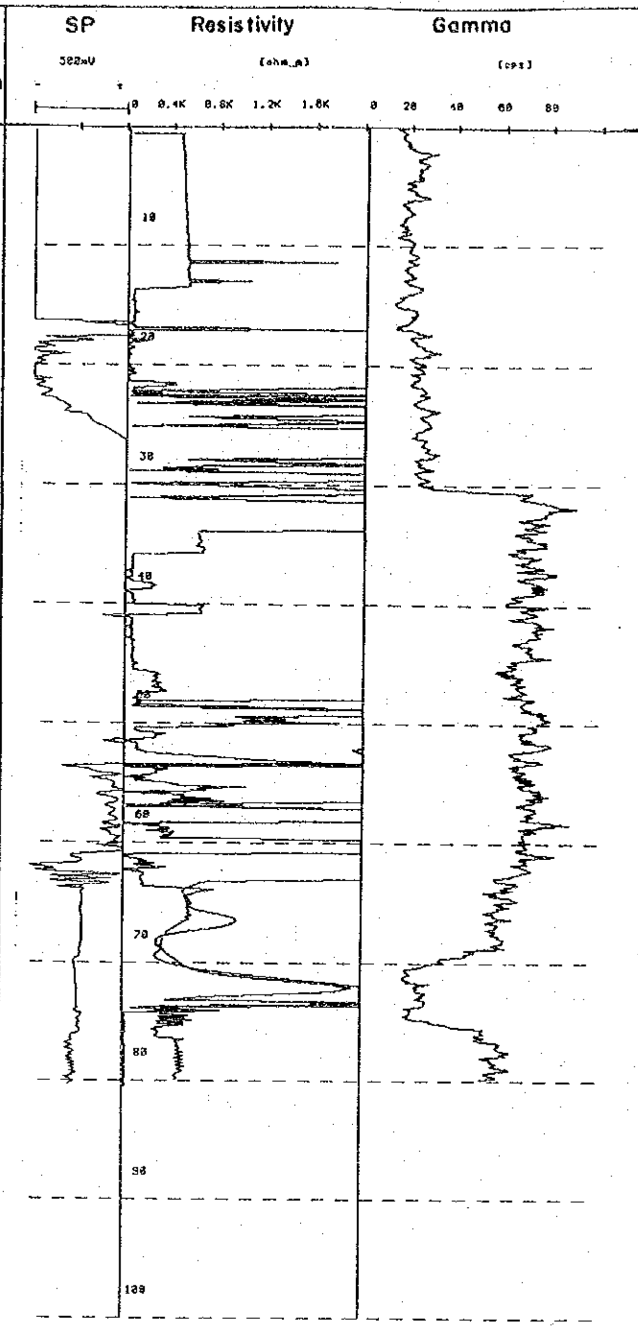
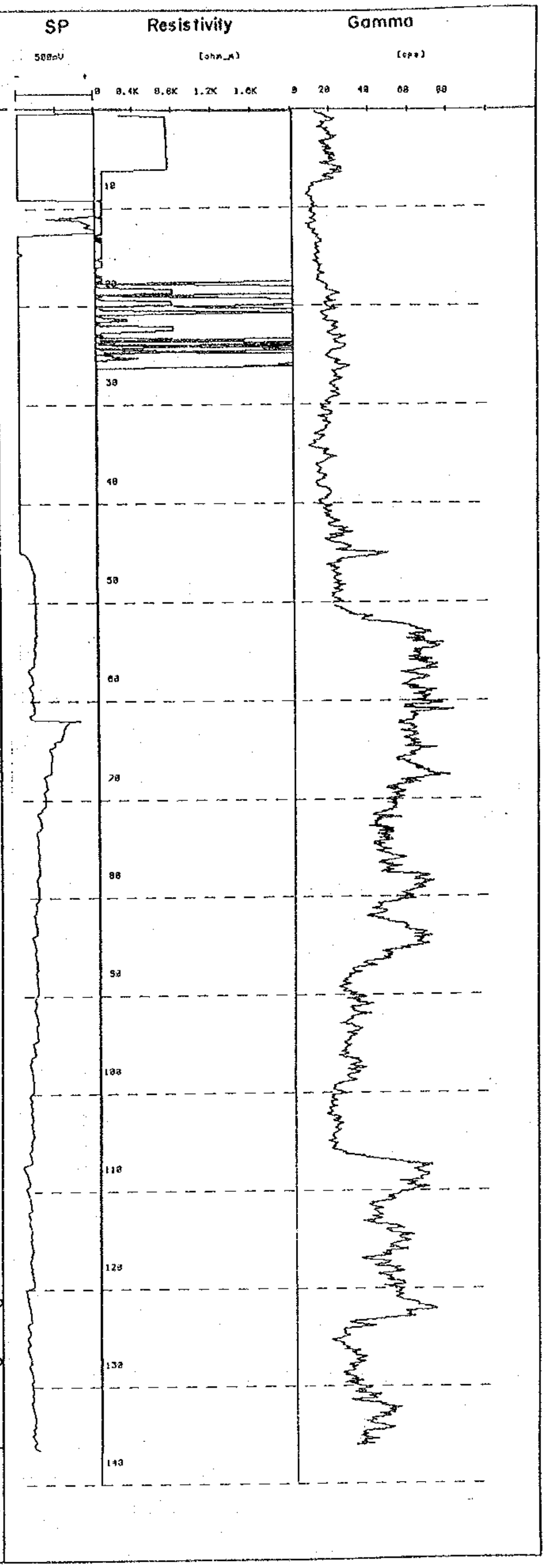


Fig. 6-20 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Maga   No. 10   (T/W)

Depth (m)	Color	Strata Description
0 – 6.0	Red-brown	Sand and Silt (Top Soil)
6.0 – 8.0	Red-brown	Hightly Weathered Quartzite
8.0 – 18.0	Red-brown	Highly Weathered Crystalline Schist
18.0 – 48.0	Yellow-brown	Weathered Crystalline Schist *Well Collapse
48.0 – 52.0	Light yellow-green	Partially Weathered Quartzite *Hard rock
52.0 – 84.0	Dark green~ Yellow-brown	Partially Weathered Crystalline Schist
84.0 – 86.0	Yellow-brown	Weathered Crystalline Schist
86.0 – 106.0	Light yellow-green	Partially Weathered Quartzite
106.0 – 123.0	Dark green	Partially Weathered Crystalline Schist
123.0 – 131.0	Light yellow-brown	Weathered Quartzite *blocky
131.0 – 135.0	Dark green	Partially Weathered Crystalline Schist
135.0 – 138.0	Yellow-white ~Clear	Partially Weathered Quartzite

Casing program:
- 4" screen: 42.0 – 45.0
- 4" casing
- 4" screen (0.5 mm): 123.0 – 129.0



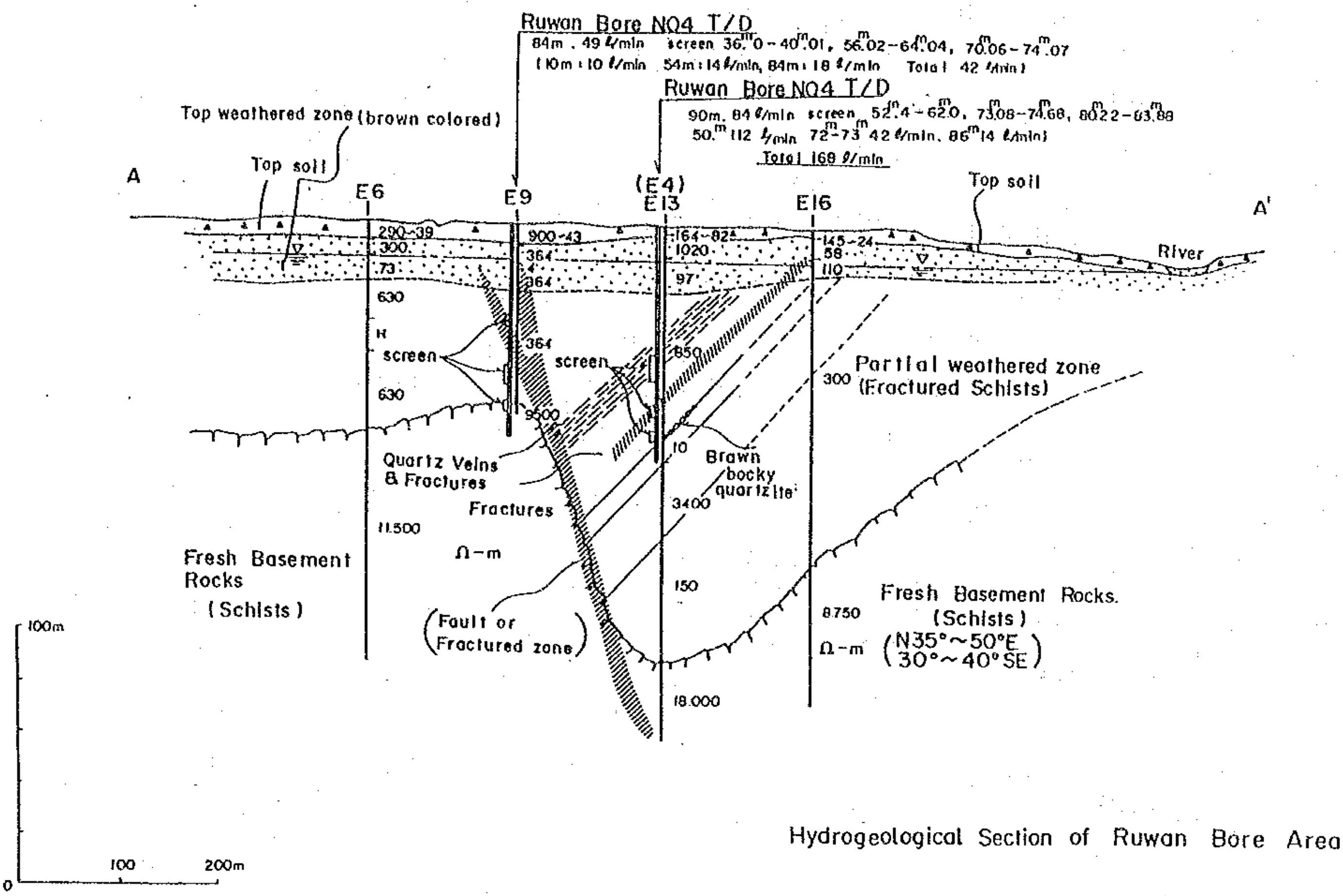


Fig. 6-21 Schematic Cross Section of the Basement Complex Area

The additional observation of core samples and/or drill cuttings and the periodical checking of the yield of water discharged from the drilling hole are very important to determine screen position and screen size. On this point, down-the-hole hammer drilling is strongly recommended for good drilling results in the basement complex area.

(Sedimentary area)

Lithologic and geophysical logs of the test boreholes and wells drilled in the sedimentary area are given in Figure 6-22.

① In the sedimentary area, a tentative general area selection for groundwater development based on specific capacity maps is an effective way to obtain good results (Figure 4-3). As for specific drilling site selection within the area, to base it on hydrogeological reconnaissance and existing borehole data, such as shown in Figures 6-23 and 6-24, is an effective way to determine detailed geophysical prospecting survey plans and tentative drilling plans.

② Carrying out of observation of core samples and carrying out of geophysical logging using a Geologer 3030-type survey meter are very useful ways to detect aquifers and aquifuges, and to determine screen position and screen size.
In the Sokoto sedimentary basin, natural gamma ray intensity of less than 5cps and electrical resistivity (long normal) of more than 150Ω-m were observed and taken to indicate good aquifers (Figure 6-22).

Fig. 6-22 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Horo Birni No.23 (T/D)

Depth (m)	Symbol	Color	Strata Description
0 – 3.0		Red	Laterite
3.0 – 20.7		White-grey	Clay
20.7 – 24.0		White-grey	Medium Sand
24.0 – 30.0		White	Clay
30.0 – 44.0		White-grey	Medium Sand
44.0 – 56.0		White-grey	Fine Sand
56.0 – 72.0		White-grey	Alternation of Sand and Clay
72.0 – 94.0		White-yellow ~Light-pink	Fine~Medium Sand
94.0 – 101.5		Black	Sandy Shale
101.5 – 140.0		Grey	Alternation of Sand and Shale
140.0 – 150.0		Black	Sandy Shale

Casing program: 4" screen (0.25 mm) 70.0 – 80.5; 4" casing

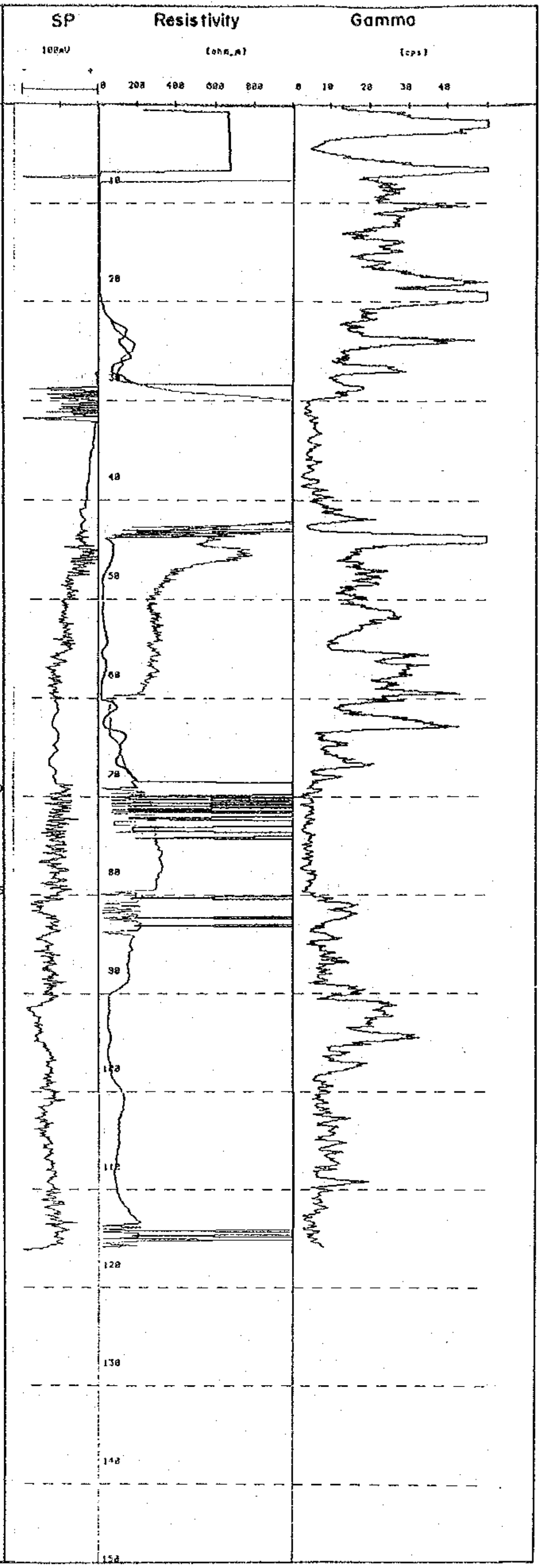


Fig. 6-22 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Horo Birni No.23 (T/W)

Depth (m)	Color	Strata Description	Casing program
0 – 3.0	Red	Laterite	6" casing
3.0 – 20.5	White-grey ~Grey	Marly Shale	6" casing
20.5 – 24.0	White-grey	Medium-Coarse Sand	6" casing
24.0 – 33.0	Grey	Marly Shale	6" casing
33.0 – 40.0	White-yellow	Coarse Sand	6" casing
40.0 – 68.0	White-yellow ~Light-brown	Alternation of Sand and Clay	6" casing
68.0 – 89.0	White-yellow	Fine to Medium Sand	6" screen (0.25 mm) 72.0 – 80.5
89.0 – 95.0		Alternation of Sand and Clay	6" casing
95.0 – 102.0	Black	Sandy Shale	6" casing
102.0 – 120.0	Grey	Alternation of Sand and Shale	6" casing

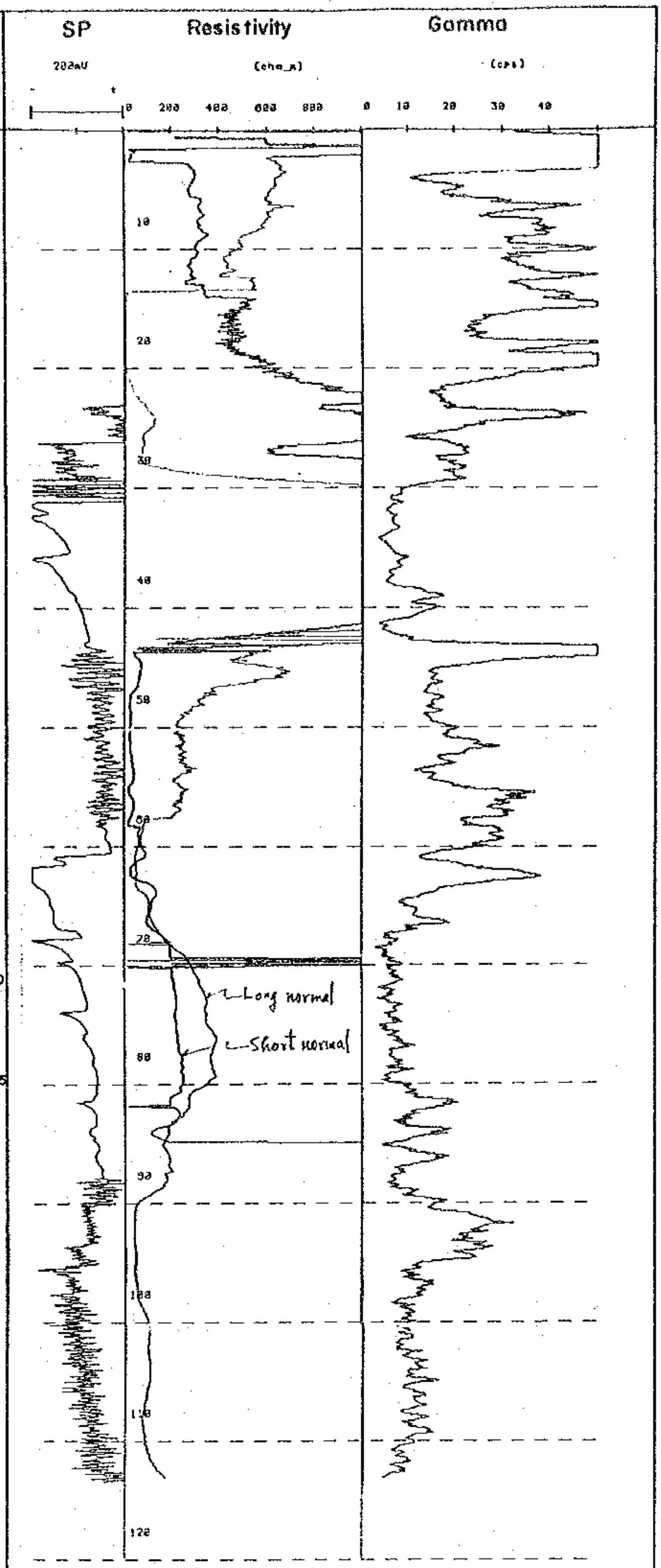


Fig. 6-2 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Soro　　No.34　　(T/W)

Depth (m)	Color	Strata Description	Casing program
5.0	Yellow	Fine Sand	6" casing
130.0	Brown	Laterite	
16.0	Yellow-brown	Clay	
25.0	Yellow-brown~ Brown	Alternation of Laterite and Clay	
34.5	White-grey	Clay	
52.0	Yellow-grey	Fine Sand	
56.0	Grey	Clay	
82.0	Yellow-grey	Medium Sand	6" screen (0.25mm) 64.6 – 76.0
88.0	Dark-blue ~Grey	Alternation of Sand and Clay	
100.0	White-grey	Clay	
124.0		Alternation of Limestone and Limeclay	
148.0	Dark blue	Clay	
150.0	Dark blue	Clay with Sand	

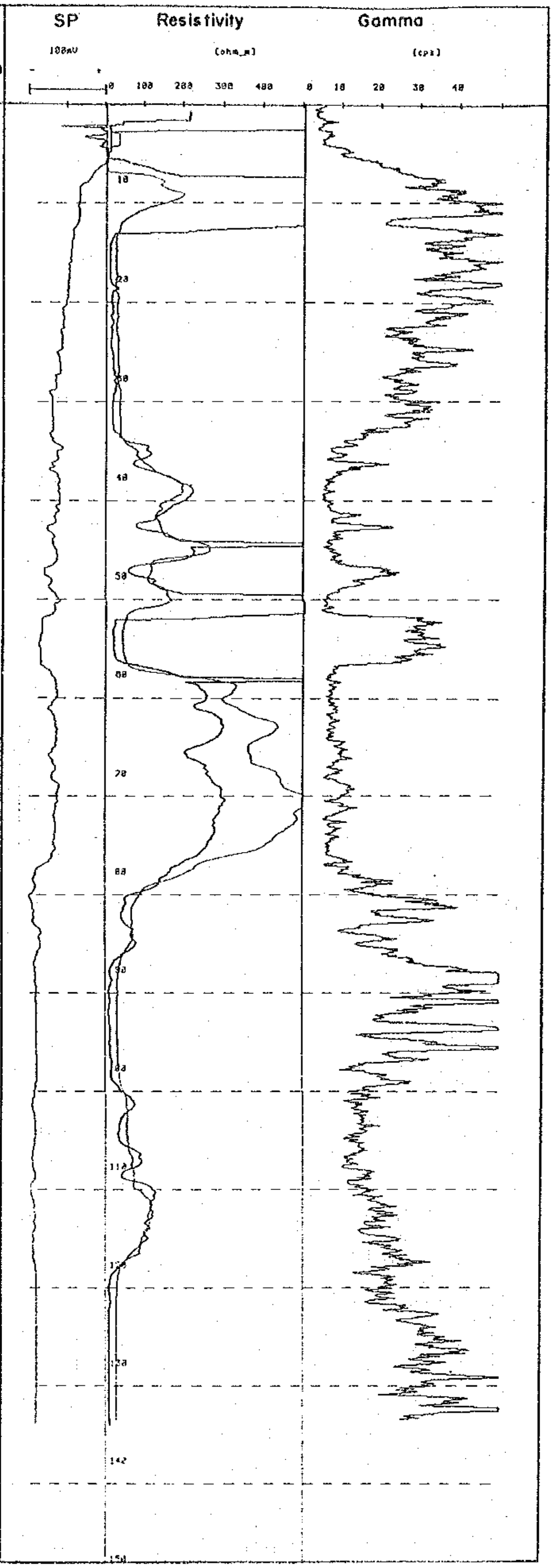
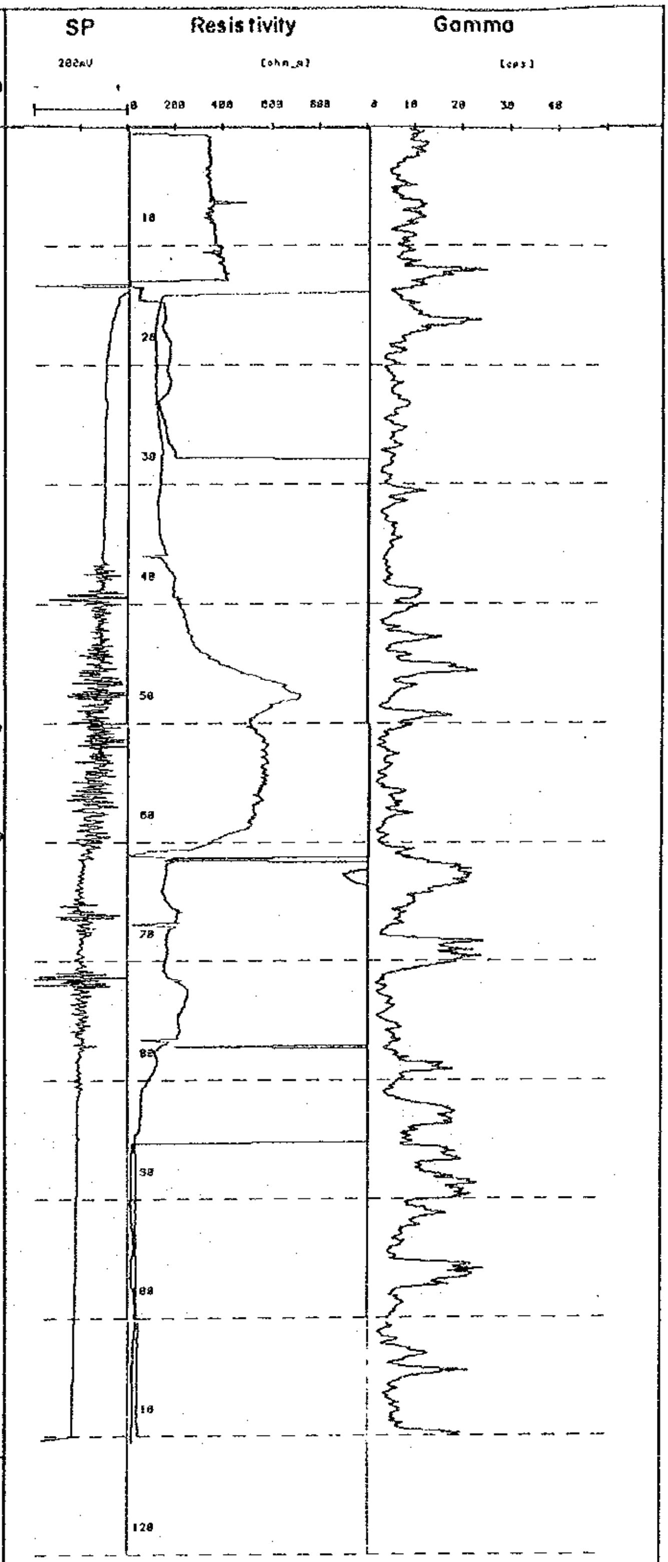


Fig. 6-22 Lithologic and Geophysical Log of Groundwater Exploration Well

Village : Kuka Koqo No.44 (T/W)

Depth (m)	Color	Strata Description
3.0	Red-brown	Fine Sand
8.0	Red-brown	Sand and Gravel
16.0	Red-brown	Coarse Sand with Gravel
19.0	Yellow-brown	Coarse Sand with Gravel
25.0	Yellow	Coarse Sand with Gravel
37.0	Yellow	Alternation of Sand and Clay
41.0	Yellow	Medium Sand (Consolidated)
44.0	White-yellow	Clay
45.0	Yellow	Coarse Sand
51.0	White-yellow	Clay
53.0	White-yellow~Brown	Sand and Gravel
54.0	Red-brown	Clay
65.0	Yellow~White-yellow	Sand and Gravel
67.0	Red-brown (dark)	Clayey Sand
69.0		Sandy Clay
70.0	Dark yellow	Coarse Sand
78.0	Red-brown (dark)	Sandy Clay
85.0	Red-brown (dark)	Fine Sand
96.0	Red-brown (dark)	Sandy Clay
98.0	Red-brown (dark)	Fine Sand
103.0	Red-brown (dark)	Sandy Clay
113.0	Grey ~Blue-grey	Alternation of Sand and Clay

Casing program: 6"screen (0.5mm) 51.0 – 60.0; 6"casing



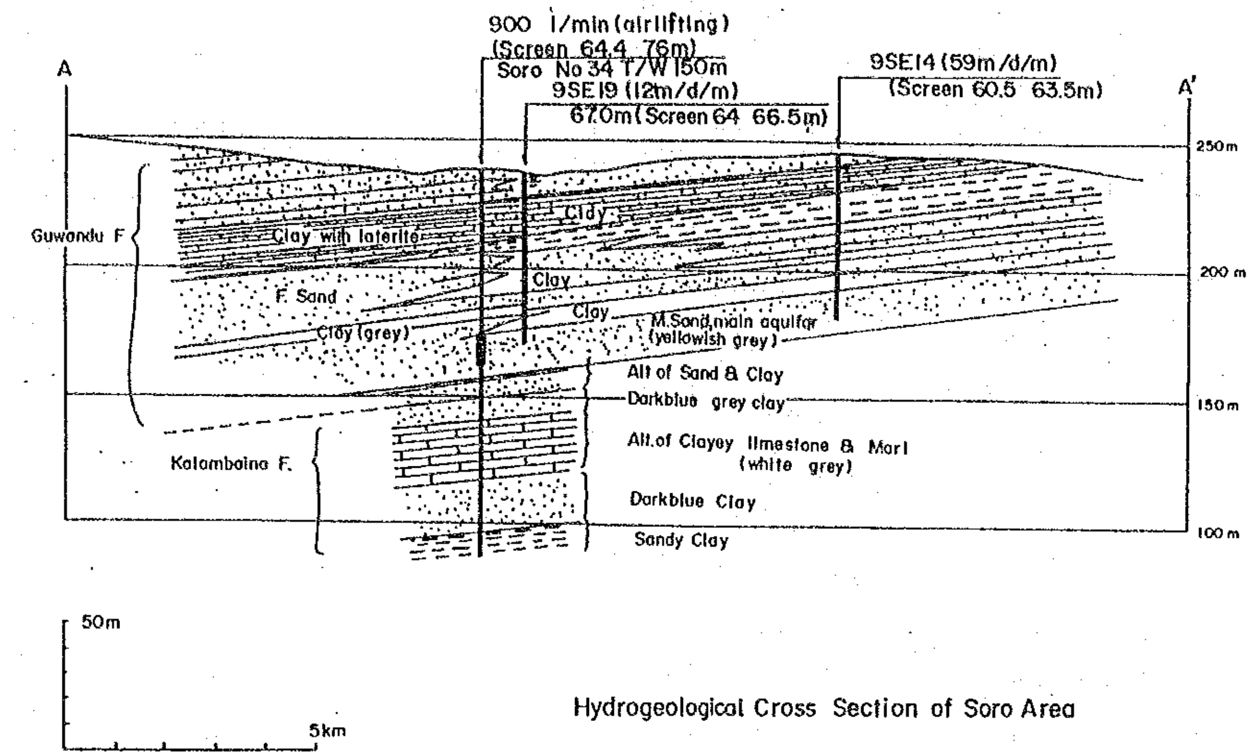


Fig. 6-23 Hydrogeological Cross Section of Soro Area

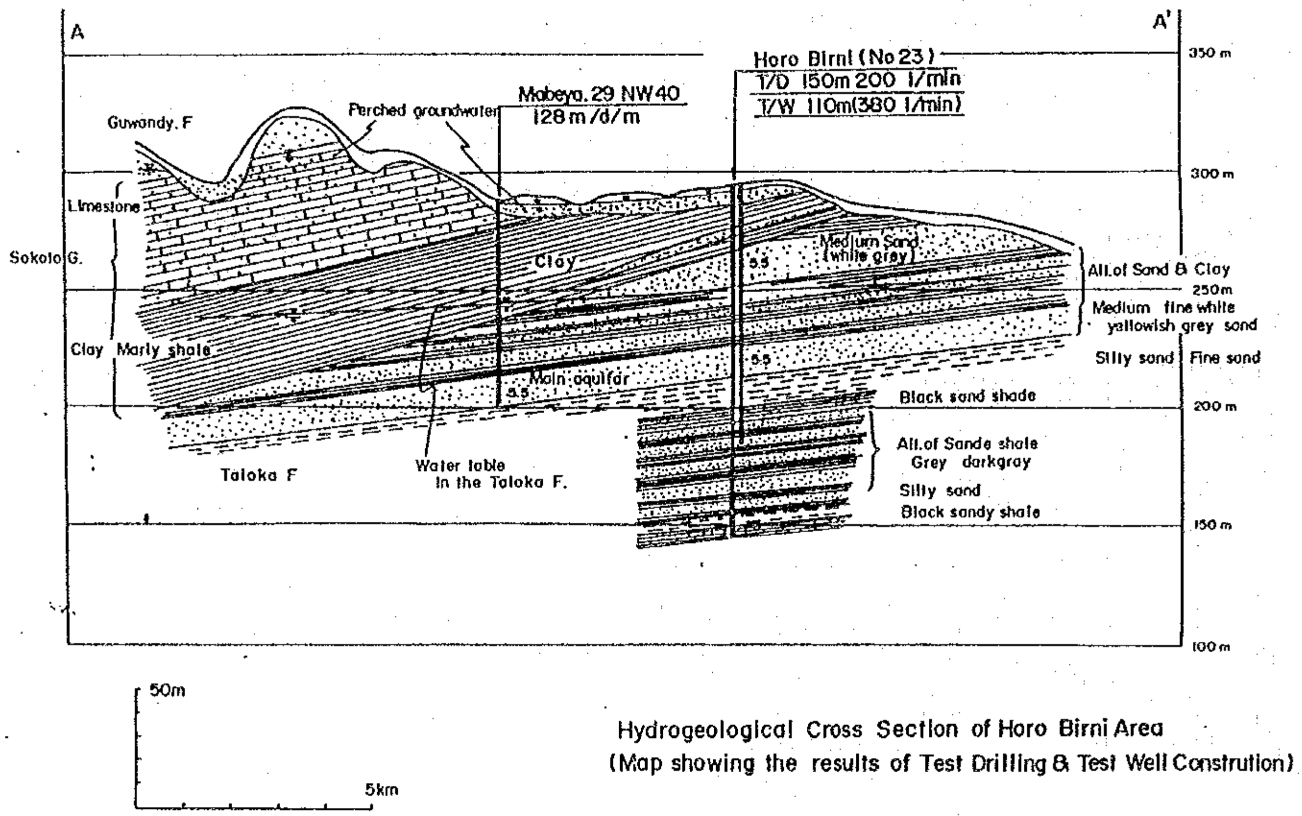


Fig. 6-24 Hydrogeological Cross Section of Horo Birni Area

6-2-4 Pumping tests

Five (5) test drilling holes and seven (7) test wells were drilled in the basement complex and sedimentary areas in order to obtain aquifer properties.
The step drawdown, the constant rate, and the recovery tests were carried out at seven test wells (boreholes) using a submersible motor pump. The number of steps, the duration of pumping, and other pumping conditions were as follows:

(1) Step drawdown test

During the test, the pumping rate was increased in five steps at regular intervals.
The pumping rate at each interval was based on the preliminary pumping test.
The duration of pumping at each step was three (3) hours.

(2) Constant rate test

This test was carried out after the step drawdown test when the water level recovered to nearly the original static level. The constant pumping rate was determined based on the results of the step drawdown test.
The duration of pumping was forty eight (48) hours.

(3) Recovery test

Recovery time measurement was carried out at regular intervals for twenty four (24) hours after constant rate pumping was stopped.

In addition to the normal pumping tests at the boreholes mentioned above, air lift pumping tests were carried out at five (5) test drilling holes.

Summary drawings of test wells and test drilling holes are shown in Figure 6-19.

Time drawdown and time recovery measurements were plotted on log and semi-log graph paper in order to calculate transmissivity, permeability, and storage coefficients.

Methods of analysis used in this Study were Theis and Jacob, which are applicable to confined aquifers in unsteady state conditions.

Table 6-10 summarizes aquifer parameters calculated through the various techniques.

6-2-5 Chemical quality test

In order to study chemical components of water, samples taken from test wells were analyzed in a laboratory.

Table 6-11 shows concentrations of principal ions contained in the water. A trilinear diagram and a pattern diagram showing the chemical component of the water are drawn from the results (Figures 6-25, 6-26). As is evident from the diagrams, most of the water is a calcium, magnesium - bicarbonate type except for the water at Ruwan- Bore which is a sodium - bicarbonate type. The total dissolved solid (TDS) ranges from a low of 42.7mg/ℓ at Kukakogo to a high of 1200mg/ℓ at Dauran. TDS at Dauran is excessively high compared with the other waters.

The TDS of water obtained in the basement complex area has a range of more than 200mg/ℓ except Maga, however it has a range of less than 50mg/ℓ in the sedimentary area.

Table 6-10 Results of Pumping Tests

Geologic Unit	Village Name	Type	Q ℓ/min	s m	Sc ℓ/min/m	Transmissivity m^2/min		
						Theis	Jacob	Recovery
Basement Complex Area	Tunga Ardo	T/D	13	12.0	1.1	—	—	—
	Ruwan Bore	T/D	70	—	—	—	—	—
	Ruwan Bore	T/W	70	38.9	1.8	$1.1*10^{-3}$	$9.9*10^{-4}$	$8.8*10^{-4}$
	Dauran	T/W	129	6.3	20.4	$2.7*10^{-2}$	$3.4*10^{-2}$	$3.4*10^{-2}$
	Yambuki	T/W	69	8.1	8.5	$5.3*10^{-3}$	$5.1*10^{-3}$	$3.0*10^{-3}$
	Yambuki	T/D	69	—	—	—	—	—
	Mage	T/W	100	57.8	1.7	$1.5*10^{-3}$	$1.3*10^{-3}$	$6.3*10^{-4}$
Sedimentary Area	Horo Birni	T/D	300	—	—	—	—	—
	Horo Birni	T/W	300	13.8	21.7	$5.4*10^{-2}$	$4.6*10^{-1}$	$5.6*10^{-1}$
	Soro	T/W	316	4.2	74.9	$9.8*10^{-2}$	$2.6*10^{-2}$	$8.3*10^{-1}$
	Kuka Kogo	T/W	316	10.1	31.3	$3.1*10^{-2}$	$3.3*10^{-2}$	$3.1*10^{-2}$

Remarks

Type : T/D Test Drilling
T/W Test Well

Q : Pumping discharge

s : Drawdown

Sc : Specific capacity

Table 6-11 Ion component of water samples

ION \ NO	DAURAN	HORO BIRNI	KUKAKOGO	MAGA	RUWAN BORE	SORO	TUNGA ARDO	YAM BUKI
Cl^- (mg/ℓ)	64.5	1.7	1.9	1.4	11.5	1.2	10.3	5.9
HCO_3^- (mg/ℓ)	354	18.3	33.3	84.9	469	37.5	569	670
SO_4^{2-} (mg/ℓ)	14.5	1.9	1.1	2.2	3.3	6.0	3.8	35.9
F^- (mg/ℓ)	0.18	0.01	0.06	0.10	0.52	0.09	0.17	0.35
Na^+ (mg/ℓ)	83.1	7.11	4.03	5.74	41.8	1.63	44.7	35.2
K^+ (mg/ℓ)	4.97	1.25	4.41	3.64	15.9	1.00	1.12	7.62
Mg^{2+} (mg/ℓ)	46.1	2.3	3.1	9.6	6.0	3.1	23.2	22.1
Ca^{2+} (mg/ℓ)	171	4.1	0.8	5.4	27.0	2.1	28.2	64.3
SiO_2 (mg/ℓ)	58.7	10.7	12.0	26.7	35.3	12.0	33.0	49.3
T.D.S (mg/ℓ)	1200	70.7	42.7	99.3	263	40.0	334	443

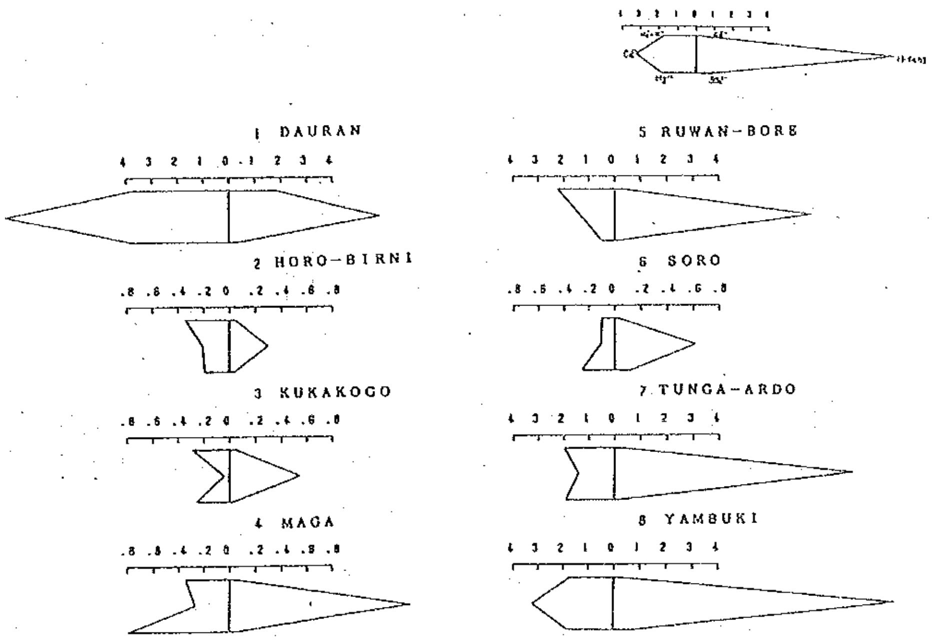


Fig.6-25 Pattern Diagrams

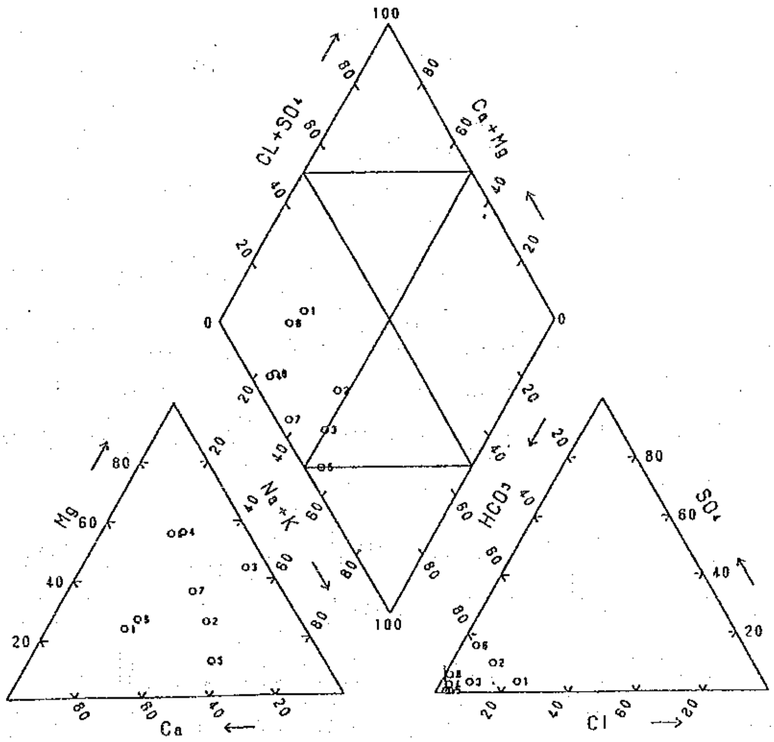


Fig.6-26 Trilinear Diagrams

6-3 Additional Experimental Survey in the Basement Area

An additional detailed hydrogeological survey was carried out in Zugu, one of the candidate villages included in the basement complex area. The purpose of this survey work was :

- to brush up the hydrogeological survey methodology
- to introduce the method of seismic refraction in hydrogeologic investigation,
- to review the method of site selection for the drilling based on the comprehensive analyses of all of the results including every different survey, and
- to establish the appropriate guideline for the groundwater investigation, particulary in the basement complex area, a so-called difficult area.

6-3-1 Survey methodology

In order to accomplish the above-mentioned purpose, the following activities were undertaken ;

- Hydrogeological field reconnaissance with remote sensing
- Survey line fixing work (checkerboard pattern with 100m intervals), and a revision of the topographic map prepared in the previous stage
- Transient electro-magnetic (TEM) survey and its rough analysis
- Electric resistivity sounding, the field operations involved, the resistivity classification by depth, and preparation of the iso-depth map of fresh bedrock, which established the major basis for determination of the drilling points
- Seismic refraction survey, the field operations involved and the explanation of the principle and analytic procedures.
- Test well construction and pumping test to confirm the lithologic formation and yielding capacity of the wells

The location of above survey and drilling points is represented in Figure 6-27.

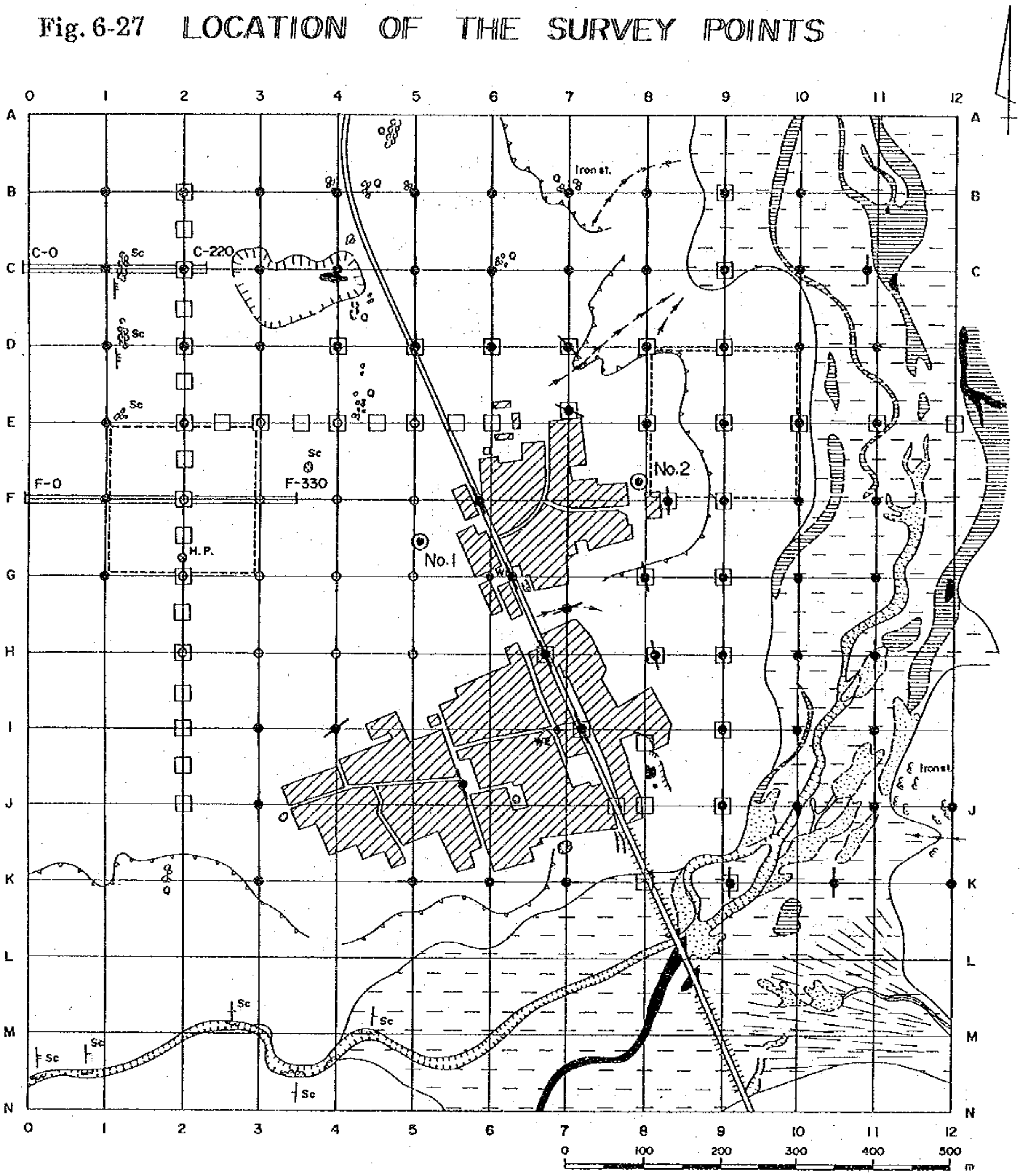
6-3-2 Survey results

The contents of the work are tabulated in the following table, and the detailed findings/results of the work of each survey are as follows.

Table 6-12 The additional hydrogeological survey conducted in Zugu

Work Item		Amount
Remote sensing	LANDSAT image analysis	1 scene of pan-chro mode image covering 400km²
	Aerial photograph interpretation	1 pair of photographs covering about 20 km²
Hydrogeological field reconnaissance		The village and its surroundings, 3km²
Survey line setting		Checkerboard pattern with 100m intervals, 1.02km²
Geophysical prospecting	Electric resistivity sounding	77 points with max. depth of 200m, with average at 180m
	Transient electro-magnetic survey	2 transmitting loops, each with 30 receiving points
	Seismic refraction survey	2 lines, total length 545m, with 5m detection intervals
Test drilling and pumping test	No.1 drilling and pumping test	130m and 120m driling with 4"casing, Hand pump setting
	No.2 drilling and pumping test	

Fig. 6-27 LOCATION OF THE SURVEY POINTS



Electlic Sounding

- surveyed point
- surveyed in previous stage

Seismic Refraction Survey

C-0 C-220 survey line

TEM Survey

- measured point
- transmitting loop

Test Drilling

- No.1, 2 drilling point

(1) Topographic features around Zugu Area

The village Zugu is situated on a peneplain, which widely extends north-westward, near the confluence of the two rivers, one flowing from west to east in the southern part of the village and the other from south to north in the eastern part of the village.

Both of the rivers are accompanied by the so-called "fadama", which is a flat area with recent river deposits, at a width of 200 to 400m, near the village. The elevation difference between the village ground and the riverbed ranges from 6 to 14m, and the edge of this peneplain is connected to the riverbed by a gentle slope of a 2° to 7° inclination.

The wide fadama of the eastern side of the village extends more than 8 km to the north (lower part), while it sharply narrows down near the village in the south (upper stream side). The southern river of the village has a clear course of river flow up to the portion at the highway bridge, and a rapid water flow carries soil and sand downstream in the rainy season. However, the flow course suddenly becomes unclear after crossing the highway, due to the expansion of the flood plain from here, which is gradually assimilated to the fadama.

The above topographic features are represented in Figure 6-28. The contour line of every 1m interval in this map shows the relative height, based on the zero-meter height at the existing well (W2) at the village center.

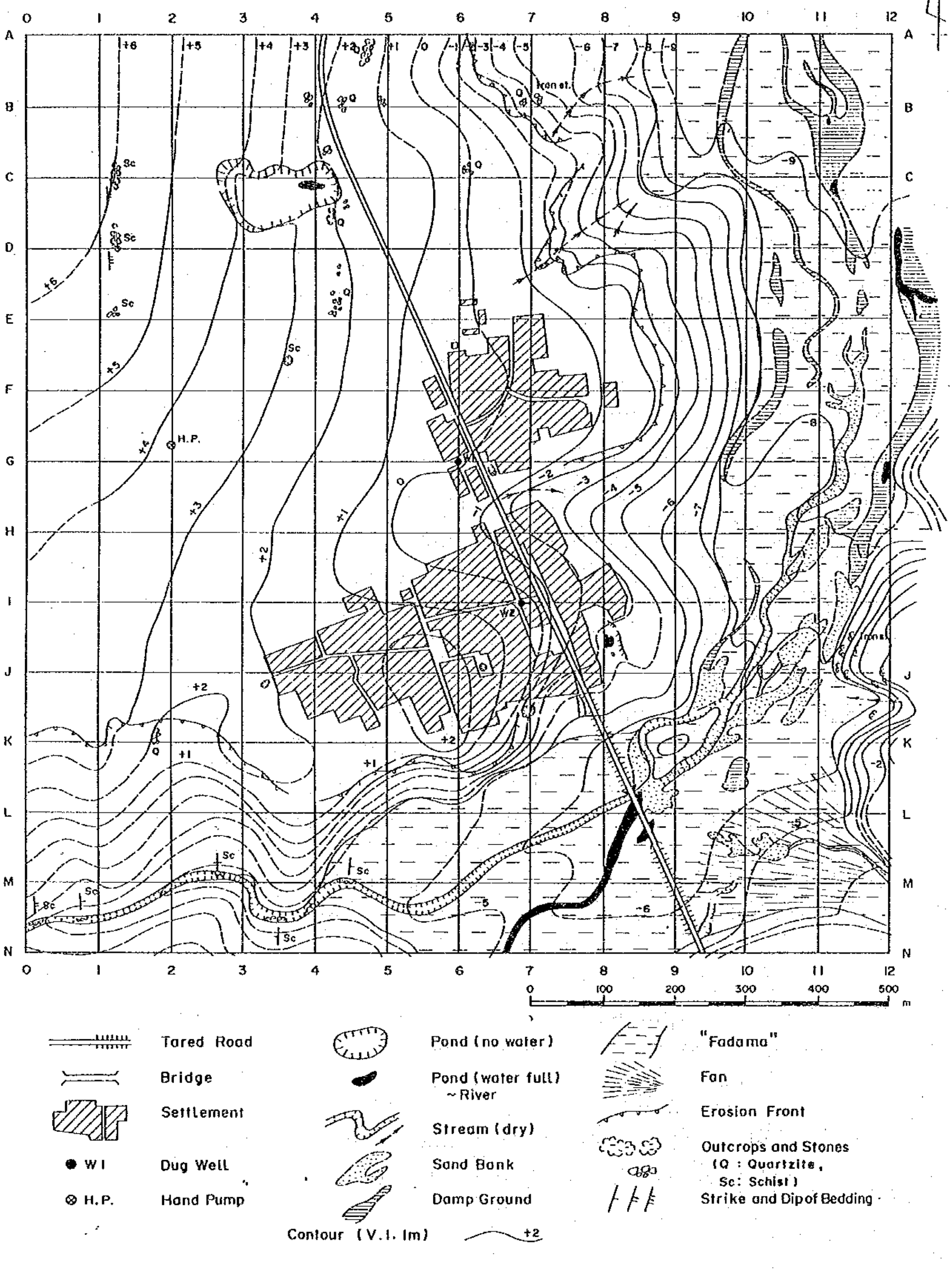
(2) Hydrogeological features revealed through remote sensing and field geological reconnaissance

① Results of LANDSAT image and aero-photo interpretation

An extensive distribution of the quartzite belt in the area between Zugu and Rijau, to the south of the concerned area, has a distinguished ridge structure, and is clearly observed on the LANDSAT image as a definite and characteristic lineament extending in a NNW-SSE direction.

However, differing from the above-mentioned southern area, in Zugu and its surroundings, the lineament is not clear.

Fig. 6-28 GEOGRAPHICAL MAP OF ZUGU VILLAGE



Especially in the eastern part of this area, no particular lineament of quartzite is observed, and the direction of the minor and inconspicuous lineaments which predominate are NNE-SSW and N-S.

On the other hand, in the western part of this area, the direction of the lineament is NNW-SSE, conforming with that of the above southern area, although the structural pattern is not so conspicuous as in the southern area.

The lineaments of different directions in the eastern area suggest a different composition of rocks, which it is likely to be predominantly meta sediment rock. The same direction of lineaments without a distinguished ridge structure suggests that the rocks in the western area are classified in the same group as those of the southern area but the composition is predominanly meta-sediment rather than the typical alternation of quartzite and meta-sediment.

A distribution area of recent river deposit, a so-called "fadama", is also visible on the LANDSAT image and aerial photographs. A wide fadama extending far down to the lower part of the river is observed on the eastern side of the village, but a wide fadama is not present at the upstream side of this river near the village nor along the southern river flowing from the west to east, which joins the eastern river near the village. This distribution pattern of the fadama suggests a difference in resistance of the basement rock by area against weathering and erosion, that is to say, that the rocks beneath the fadama sediment were more likely eroded due to a higher degree of weathering than in other places.

A poor differential erosion suggested by inconspicuous lineament in the eastern part of the area gives us a hint of a predominantly meta-sediment rock distribution in the area, and also a hint of sediment-originated quartzite intercalated in meta-sediment. In addition to this, the incontinuous distribution of the fadama suggests a highly weathered rock beneath it. Consequently, the groundwater potential is predicted to be higher in the eastern area (along the fadama) than in the western area. In addition another point of view suggests higher probability of water recharge near the fadama.

The topographic and geological features interpreted from the LANDSAT image and the aerial photographs are represented in Figure 6-29.

② Results of hydrogeological field reconnaissance

The site is composed mainly of sericite schist, a meta-sediment rock, and partially of quartzite. Since quartzite is observed to be intercalated in schist in a condition of alternation, this rock is presumed to originate from sediment, whereas it is usually found as a dyke or vein everywhere in the basement complex area.

Te schistosity of the rock strikes N-S to NNE-SSW conforming to the direction of the photo-lineaments, with a regular variation of dipping in accordance with a gentle folding structure. The part of sericite schist in the alternation has many joints along the schistosity, and it is easily separated at the joints, while joints are seldom seen in quartzite.

The ground surface of the peneplain is known to be commonly composed of a weathered crust covered with the lateritized soil. The peneplain in this area, however, has sporadic outcrops of comparatively fresh quartzite and schist in the north and northwest, which suggest that the weathering crust is thinner in the north and west than that in the south and southeast.

The eastern half of the village is covered with the secondary deposits of the weathered rocks, and this capping layer preserves the weathering crust from erosion, so that the thickness of the weathered basement rock is presumed to be larger than that of the outcropping area.

The groundwater level in the existing wells in the village is 10 to 12m below ground surface, which are 2 to 4m lower than the water level of the crescent ponds in the fadama. This fact suggests that water of the underflow channel or conduit of the fadama is the major recharge source of the groundwater around here.

③ Survey line establishment

Eleven E-W, 1km-long survey lines were fixed at intervals of 100m in the area covering the settlement area of Zugu village and its surroundings. The wooden pegs marked with the line names (A, B, ··· K) and distances from the west end of the lines were installed on the lines at every 100m interval so that the pegs formed a checkerboard pattern.

A transit compass with a tripod was used for aligning the direction of the lines.

A level survey was conducted along the lines to prepare a contourline map of the area as shown in Figures 6-27 and 6-29.

④ Electric resistivity sounding

In addition to the 15 points of the resistivity sounding conducted in the previous detailed survey, 77 points of measurement were taken, expanding the survey area to the north, east and south. The resistivity values of the recent deposits along the river range from several ten to several hundred ohm-meter and those of weathered basement rock fall in a similar range. Therefore, it is somehow difficult to distinguish them from one another by the value of resistivity.

On the other hand, the difference of resistivity values between weathered and fresh basement rock is clear, since the fresh rock has much higher resistivity, usually more than 1,000 and occasionally more than 10,000 ohm-meter. The resistivity values of the very fresh basement rock, mica schist and meta quartzite in this area, range from 10,000 to 20,000 ohm-meter and the values decrease along with the increasing frequency of cracks or that of the degree of decomposition. Thus, it is difficult to define fresh rock only by the resistivity value. However, the rock with resistivity higher than 1,000 ohm-meter, was classified as "fresh rock", based on the comparison between rock samples and the measured resistivity value.

Consequently, the iso-depth map of the fresh basement rock was prepared in the same manner as in the previous detailed survey as shown in Figure 6-30.

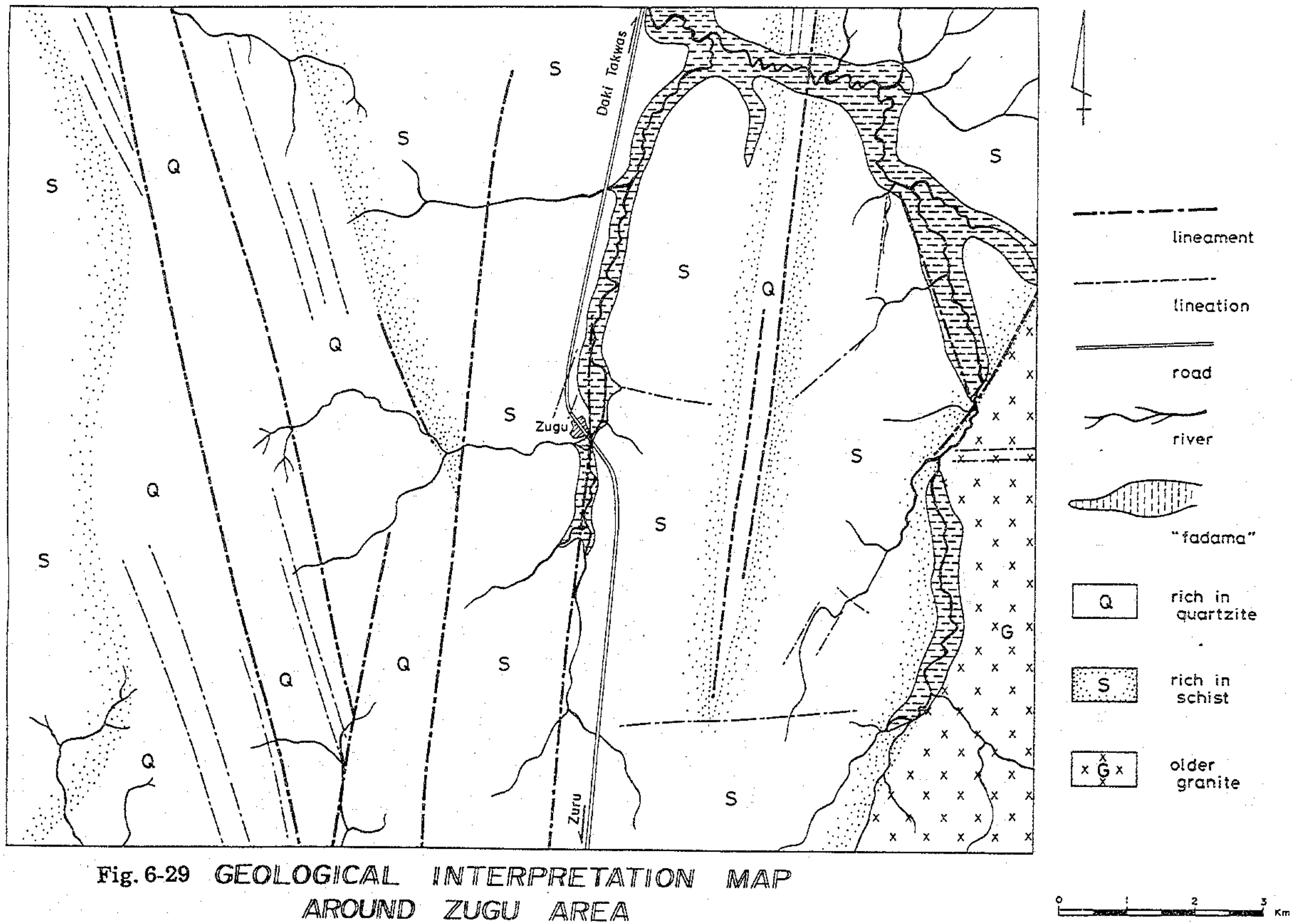


Fig. 6-29 GEOLOGICAL INTERPRETATION MAP AROUND ZUGU AREA

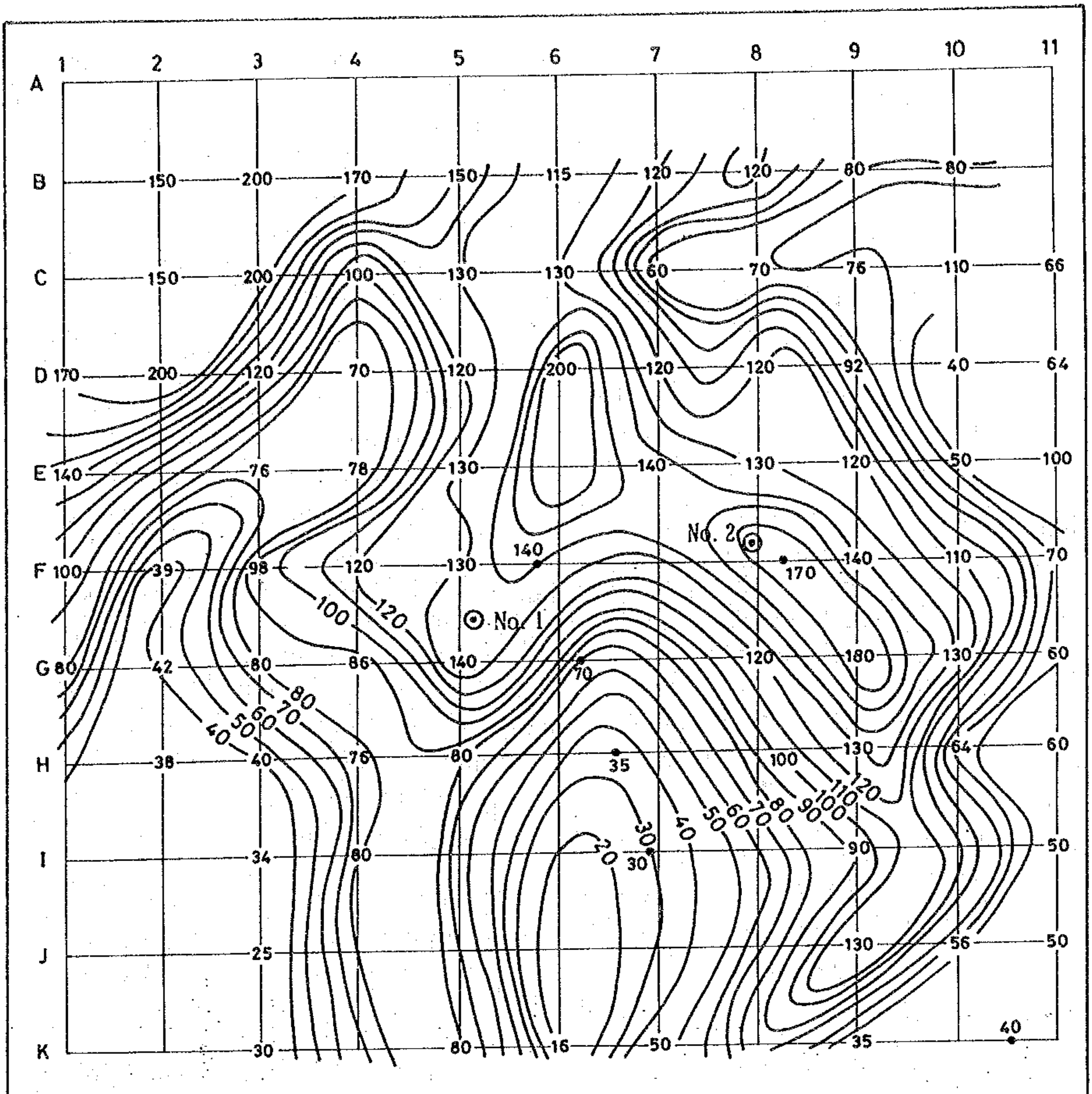


Fig. 6-30 Iso-depth map to the fresh basement rock

⊙ Drilling Point

⑤ Transient electro-magnetic (TEM) survey

A 200m-sided square loop for TEM signal transmission was laid on the surface of the ground, and the receiving station was moved along the line to take a series of measurements.

The measurements at the center of the loop made it possible to approximately classify the resistivity of the earth by depth, and the series of electric potential measurements on and outside of the loop provided the resistivity profiles along the line.

For loop A centered at F-2, the 3 lines of traverse measurement were taken, and apparent resistivity values have been plotted(Figure 6-31). Among these lines, the N-S line (from B-2 to J-2) has not shown any distinguished variation, but both of the E-W lines have shown remarkable decrease in value towards the east. This fact suggests the existence of a NEW-SES fractured zone or a V-shaped steep and deep valley of the fresh basement rock, near the east end of the measured lines.

For loop B centered at E-9, the obtained values from the 4 lines are represented in Figure6-32. A distinguished anomaly (low potential) is found near the west end of the 2 E-W lines, which is conformable to the anomaly found on the lines attached to loop A. Figure6-33, which represents the TEM profile clearly, shows the above-mentioned anomaly.

The other anomalies in relation to loop B have been also found at the south end, the east end and the north end of the lines. Among them, the south and east ones may be related to a river, probably to the buried ancient river.

At the center of the loops A and B, the average resistivity by depth has been classified as follows,

A (F-2) : Surface to a depth of about 50m : 800 ohm-meter
Deeper than 50m to unknown depth : 1200 ohm-meter

B (E-9) : Surface to a depth of about 25m : 1500 ohm-meter
25 to 125m depth : 125 ohm-meter
Deeper than 125m : 800 ohm-meter

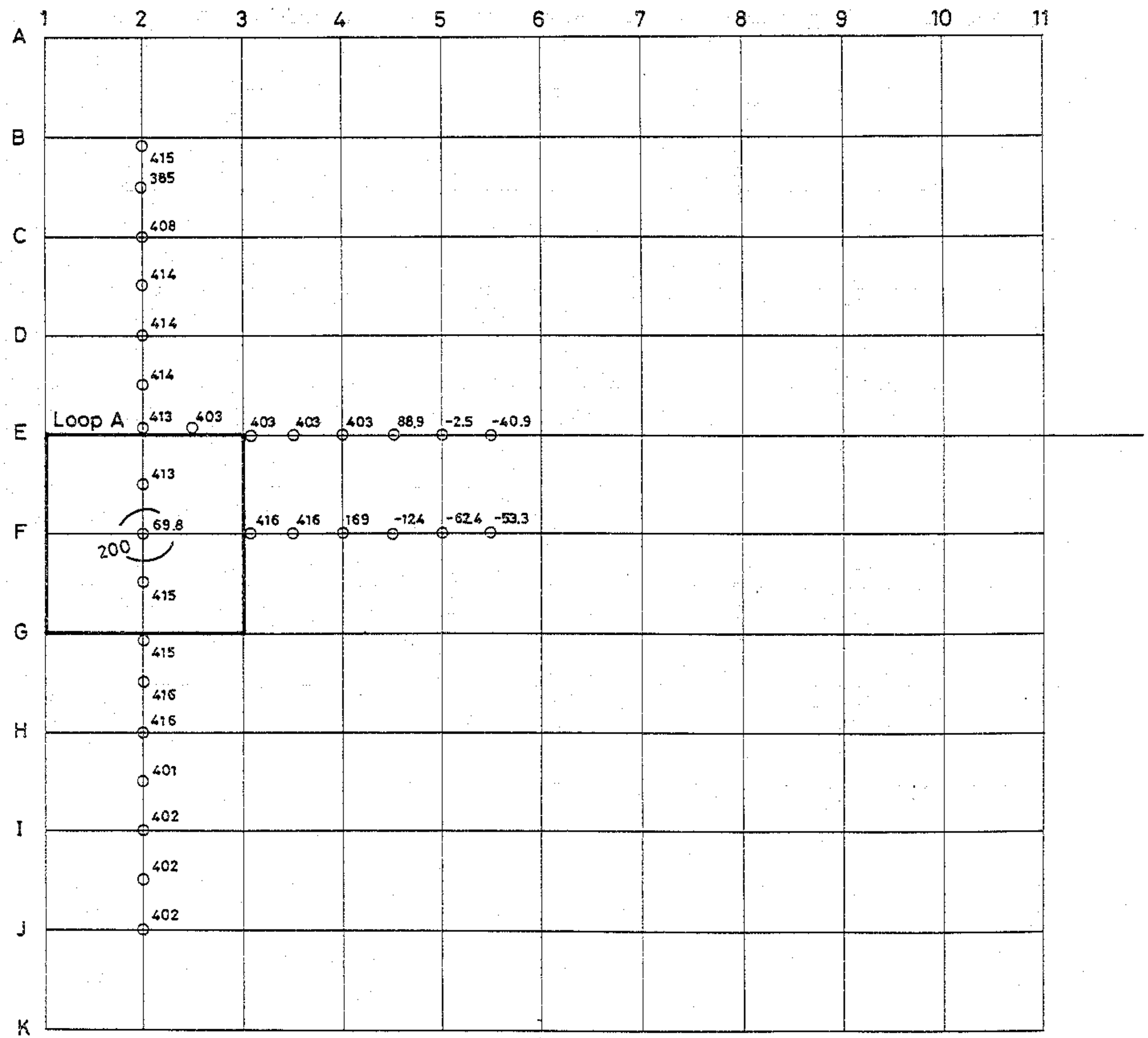


Fig. 6-31 Apparent resistivity value map (Loop A, Ch.1) (mV/A)

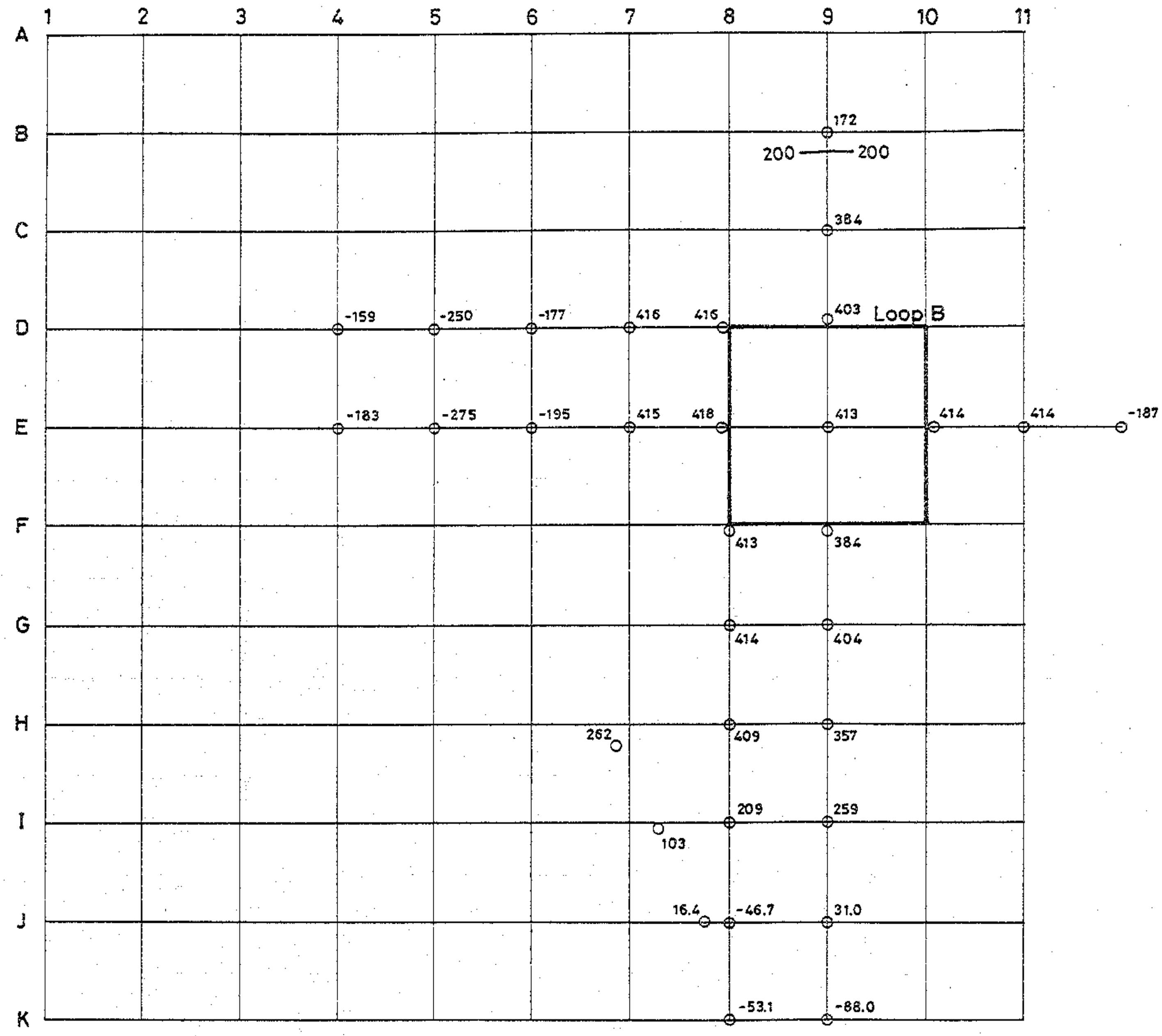
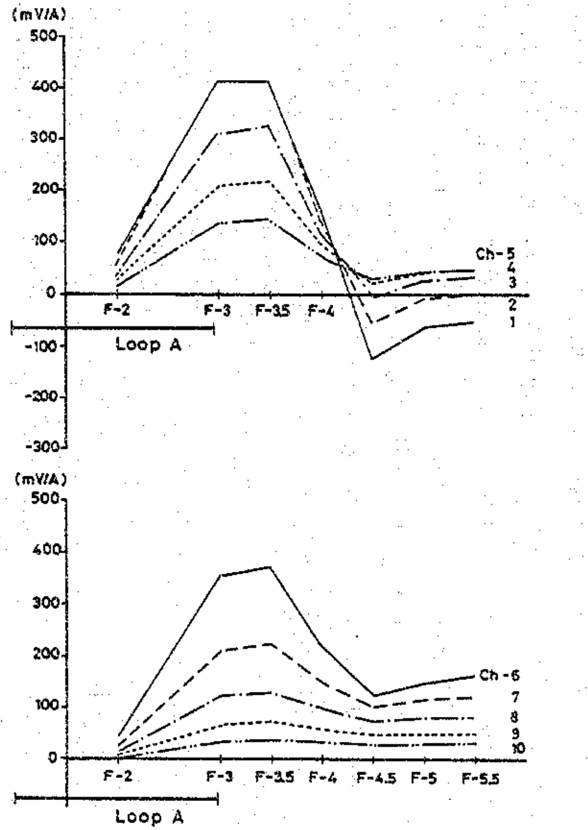
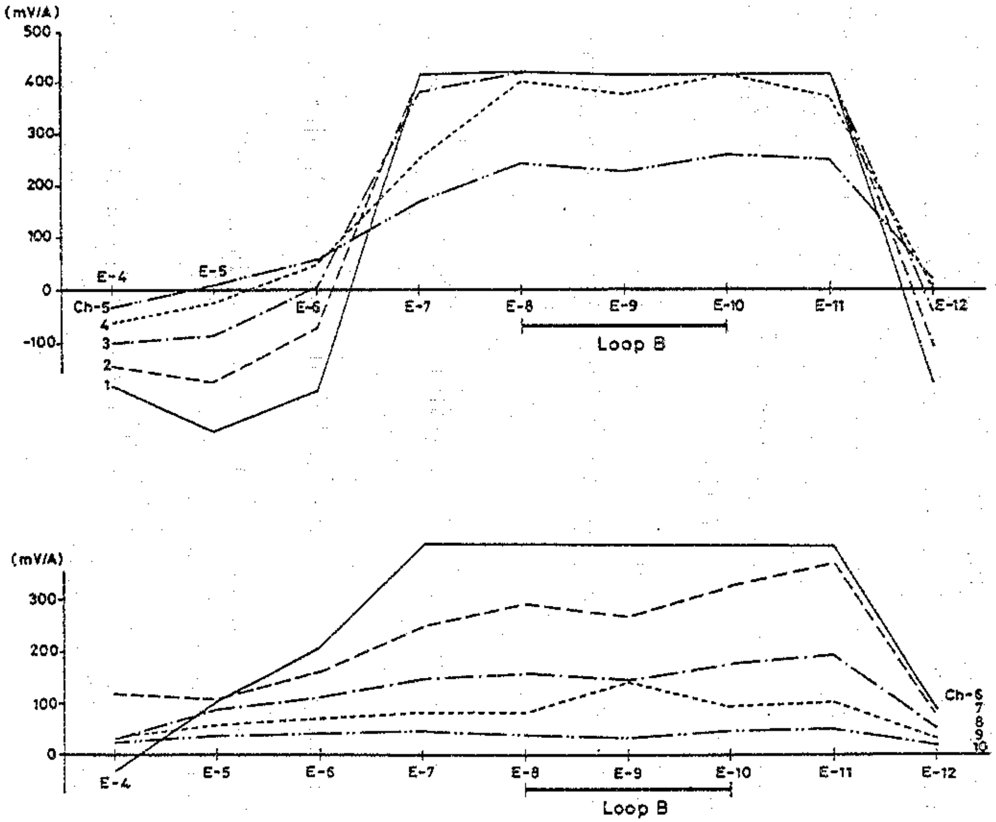


Fig. 6-32 Apparent resistivity value map (Loop B, Ch.1) (mV/A)



TEM Profile along Line F above: Ch.1~5
based at F-2 (Loop A) below: Ch.6~10



TEM Profile along Line E above: Ch.1~5
based at E-9 (Loop B) below: Ch.6~10

Fig. 6-33 The traverse data along Line E and F

According to the two-dimensional interpretation by use of the MOTEM program, the quasi-model along line F from loop A and along line E from loop B will likely match the following conditions respectively.

Line F : A conductive body, i.e. ,low resistivity material, for instance, a decomposed portion of the rock or a crack-concentrated structural line, exists beneath the receiving points of F-4, beginning at a 50m depth.

Line E : The conductive bodies exist between E-6 and E-7 and between E-11 and E-12 beneath the ground beginning at a 125m depth.

⑥ Seismic refraction survey

Intended to be carried out before the beginning of the field operations, this survey was to be for the following purposes;

a. to classify the degree of weathering of weathered crust by depth

b. to detect the exact location of partially decomposed zone or fissure concentrated structural lines

c. comparison of the above results with the results obtained from other types of geophysical surveys to site the test drilling points, and

d. technology transference on the seismic refraction survey to the Nigerian counterpart engineers.

However, since the major equipment for the survey was not functioning well during the period concerned, probably due to some trouble during transportation, the intended survey work could not be attained effectively. The field operation method was, however, introduced to a limited number of the counterpart staff time to time parallel with other geophysical surveys, and the techniques for the field operations transferred and the principle/method of seismic refraction survey lectured on were as follows;

- Survey line fixing and geophone array
- shot point planning
- gain adjustment and stack-count adjustment for better record taking

- explanation on principle of refraction theory and analytic procedure of the seismic refraction survey

⑦ Test drilling and pumping test

In order to confirm the lithologic formation and promising area estimated from the results of hydrogeological surveys, and also to clarify the hydrogeologic properties of the area, two test drillings accompanied by pumping tests were carried out.

The drilling points were sited based mainly on the results of the resistivity sounding (iso-depth map of the fresh bedrock) and also with regards to the convenience for use by the inhabitants.

The handpumps were installed in these drilled boreholes for practical use of the new wells by the inhabitants of the village.

The first drilling, 15-1, was sited at a point between F-5 and G-5, and the second one, 15-2, was between E-7 and F-7 as shown in Figure 6-27.

Both points were sited in a basin or valley-shaped deep weathered portion of the basement complex, which were expected to be the most and the second most promising zones near the settlement, one each on the east side and west side of the village.

As presumed before the drilling, the drilled well sited on the eastern side nearer to the fadama was much more productive than that on the western side.

Pumping discharge of 15-2 test well was 140 ℓ/min and the specific capacity shows about $18m^3/d/m$. This result is remarkable among the yield and specific capacity of existing wells drilled in the basement complex area.

The results of the test drilling are tabulated in Table 6-13 along with the results of the pumping test, and the well log record is shown in the Data Report (Vol. 5).

The geologic section along Line F derived from resistivity sounding and test drillings is represented in Figure 6-34.

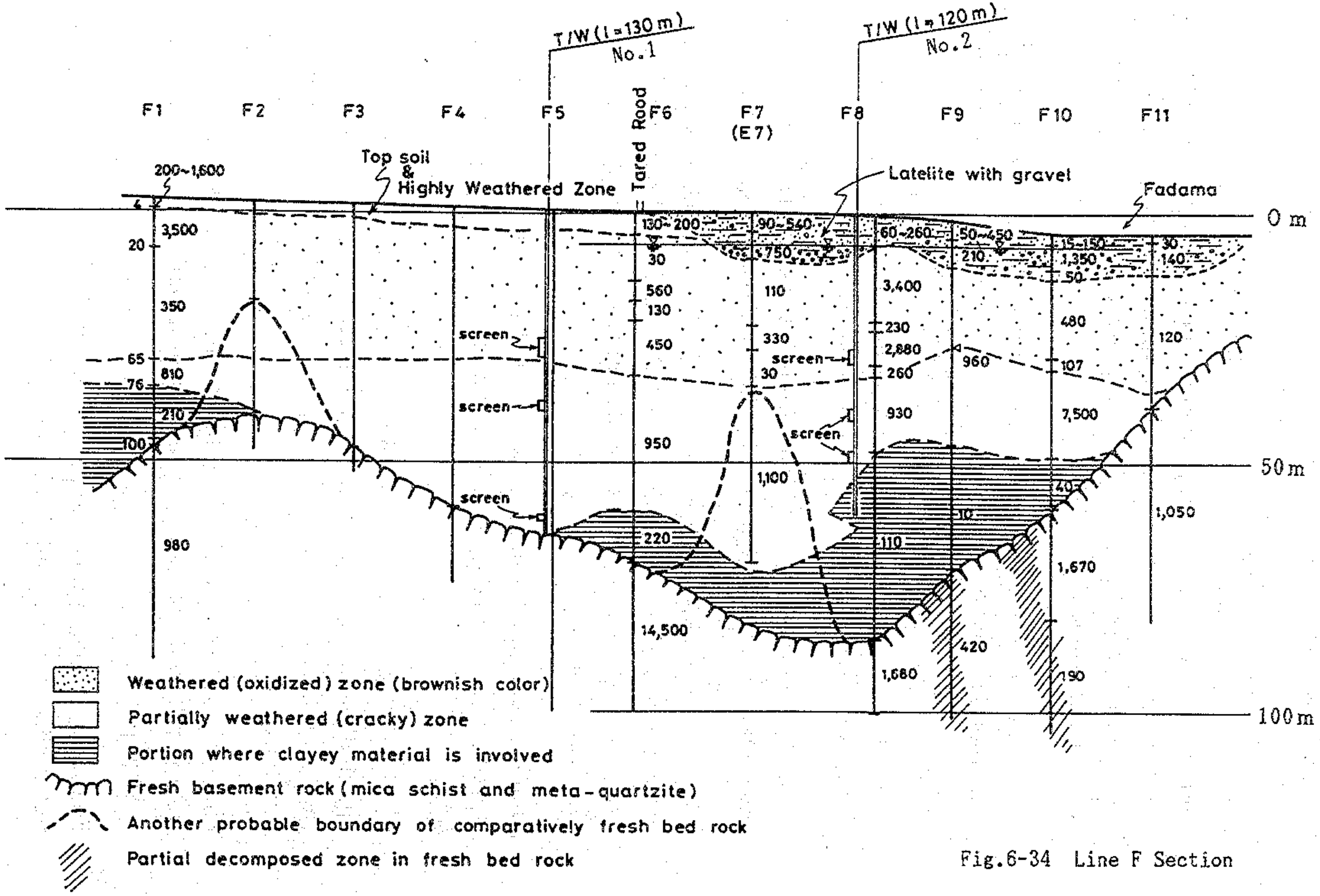


Fig.6-34 Line F Section

6-4 Guidelines for Hydrogeological Investigation

As mentioned in the previous section, many useful findings for groundwater exploration were found through comprehensive hydrogeological analysis of the results of detailed and additional experimental surveys. In particular, the findings on groundwater exploration in the basement complex area are considered to be very important because one of the major objectives of the Study is to establish an effective method of hydrogeological investigation in the so-called "difficult areas" where the basement complex is exposed.

As a conclusion, guidelines for hydrogeological investigation in the basement complex area are as shown in Figure 6-35.

As for guidelines for hydrogeological investigation in the sedimentary area, Figure 6-36 is also presented.

The histogram of the average yield of existing boreholes in the basement complex area is given in Figure 6-13. While most of the existing boreholes yielded only 10 to 15ℓ/min, most of the newly constructed boreholes, of which the drilling points were determined basically following the guidelines, yielded more than 60ℓ/min.

Table 6-13 Result of Test drilling and pumping test

Well No., Location	Drilled Depth (m)	Lithologic formation	Static water level (mBGS)	Pumping dis-charge (ℓ/min)	Draw-down (m)	Specific Capacity (m^3/day/m)	Trans-missivity (m^2/day)
15-1 F-5 | G-5	130	0~1m: Surface soil 1~45m: Top weathered (oxidation) zone of basement rocks. meta-quartzite, mica schist with quartzite vein 45~130m: Partially weathered basement rocks	14.00	28	31.7	0.61	1.05 (Jacob) 1.12 (Theis)
15-2 E-7 | F-7	120	0~1m: Lateritized soil (residual deposit) 12~17m: Gravely material 17~85m: Highly weathered basement rock 85~120m: Partially weathered basement rock	10.30	140	5.42	17.94	25.44 (Jacob) 23.80 (Theis) 23.80 (Recovery)

Figure 6-35 Guidelines for Hydrogeological Investigation for Groundwater Development in the Basement Complex Area

Preparatory work to understand the outline of the hydrological and hydrogeological conditions of the whole area	-Collection and arrangement of existing data. (Specific capacity of wells, groundwater level, water quality, etc.) -Analysis of structural lineament and drainage systems by interpretation of aerial photographs and/or LANDSAT images. -Rock type classification by area through reference to existing geological maps.

⇩

Preliminary field survey in and around the villages concerned to determine the hydrogeological conditions of individual sites	-Mapping of the village and surrounding area and geological reconnaissance, especially focusing on rock facies (rock type and degree of weathering) and existence of dykes and veins of quartzite, aplite or pegmatite -Measurement of water level in existing wells and questioning the inhabitants about seasonal water level variation. -A preliminary geophysical survey to confirm weathering conditions.

⇩

Geophysical surveys at individual sites, with as many survey points as possible in order to differentiate areas with higher groundwater potential	-Fixing of survey lines in 100m grid for electric resistivity soundings, and/or 200 to 400m grid for transient electro-magnetic survey. When it comes to conduct a seismic refraction survey, the survey lines should be determined by the results of the above, with wave detecting points of 5m intervals. -Existent data acquisition on the sites, and preliminary analysis of depth to fresh bedrock. -Preparation of contour line maps of fresh basement rock. -Preparation of geological cross sections along the lines which represent the hydrogeological characteristics of the site in order to justify location and depth of the wells to be drilled.

⇩

Test drillings or test well construction accompanied by logging and pumping tests to confirm geologic composition of the site as well as hydrogeological characteristics	-One or two drillings at a location where gw potential is presumed to be particularly high (deep weathered portion with basin structure or V-shaped valley of fresh bedrock, or with a concentration of veins or dykes. Test well may be used as a production well. -Depth of drilling should be down to fresh bedrock, with a casing diameter not smaller than 4" for the pumping tests to be done properly. -During drilling, drill cuttings should be carefully observed for a complete geologic log. -Based on geologic log and results of pumping test, the geological cross sections prepared above should be revised.

⇩

Planning and designing groundwater development and water supply system construction for village	-Point sources·········At the areas of very poor gw potential where critical pumpage is limited to less than several tens of liters per-minute, point sources with deep-well hand-pumps are recommended. The number of wells to be constructed depends on the population of the village (One well may serve perhaps 500 persons) and also on distribution of comparatively higher potential sites. -Semi-urban-type water supply system, i.e., wells with motor powered-pumps, elevated reservoir tanks with gravity-type distribution and a number of communal faucets·········Number of wells and capacity of reservoir tank depend mostly on capacity of wells and population to be served.

Figure 6-36 Guideline for Hydrogeological Investigation for Groundwater Development in the Sedimentary Area.

Preparatory work to understand the outline of hydrological and hydro-geological conditions of the area

- Tentative evaluation of groundwater resource potential of the area by "Specific Capacity Map"
- Collection and arrangement of existing hydrogeological and hydrological data.
- Preparation of a preliminary hydrogeological cross section of the area

⇩

Hydrogeological field survey in and around the candidate villages

- Mapping of the villages and surrounding area and geological reconnaissance.
- Measurement of water level in existing wells and questioning the inhabitants about seasonal water level variation.
- Electrical resistivity sounding, of which survey lines cut mostly straight across the strikes of the geological formations, with 6 to 8 survey points on the line spaced 100 to 200m.
- Preparation of hydrogeological section along the line in order to justify location and depth of the wells to be drilled.

⇩

Test drilling or test well construction accompanied with logging and pumping tests to confirm geologic composition of the site as well as hydro-geological characteristics

- One drilling at a location where groundwater potential is presumed to be particularly high.
- Continuous drilling work through out of day and night is generally recommended to obtain good results, accompanied by proper control of mud-water.
- During drilling, drill cuttings should be carefully observed to complete lithologic log and to determine screen position and screen size.
- As for geophysical logging, natural gamma ray intensity of less than 5cps and electrical resistivity (long normal) of more than 150Ω-m are generally taken to indicate good aquifers.
- Based on lithologic and geophysical log and results of pumping test, the hydrogeological sections prepared above should be revised.

⇩

Planning and designing groundwater development and water supply system construction. The number of wells should be comprehensively examined based on viewpoints of not only population to be served but also on optimal groundwater mining of the area.

7. EVALUATION OF GROUNDWATER RESOURCES

In order to promote water usage through groundwater development in Sokoto State, the regional hydrogeology must be correctly understood and its quantitative analysis must be carried out. In addition, the conditions for the establishment of a proper development scale must be made clear. For this, this section firstly gives a basic summary regarding the quantitative analysis of the groundwater resources. Then it examines the water balance based on the hydrogeology of the entire Sokoto State as the basis of the quantitative analysis, and finally analyzes the groundwater recharge in order to determine its capacity. In addition, particularly regarding the sedimentary rock area, groundwater simulation was carried out and the regional groundwater flow and the water balance are studied in detail here.

For the basement rock area, the yield was evaluated qualitatively based on the water balance analysis. For the sedimentary rock area, the yield was evaluated based on the water level predictions, according to the groundwater simulation.

7-1 Basic Concept on Quantitative Evaluation

The terms used in groundwater quantitative analysis are "storage capacity" and "yield". The storage capacity generally refers to the total capacity of groundwater which can be held in an aquifer or in a groundwater basin. The yield refers to the amount of groundwater which can be taken from an aquifer or from a groundwater basin by human activities.

In general, in relation to the qualitative evaluation of the groundwater resources, the yield which responds to the decline in groundwater level creates a problem, whereas the absolute value of the storage capacity is not such a problem.

Yield is classified into the next two general categories.

(1) Sustained yield

This is defined as the "groundwater amount which can be withdrawn from a groundwater basin continuously, without any undesired results" (Todd, 1959). In general, the term "safe yield" is used in place of this.
"Undesired results" refers to an increase in pumping costs due to decline in the groundwater level,the occurrence of land subsidence and seawater intrusion.

This definition includes 2 criteria :

(a) the water balance can be maintained perennially
(b) there are no economic nor groundwater accident risks.

With importance placed on the criteria pointed out in a), the term "perennial yield" can also be employed (Todd, 1980).

(2) Mining yield

This is defined based on the premise that groundwater is like irreplaceable resources such as oil and natural gas. Groundwater is exhausted and perennial usage is not possible. Groundwater of this kind of condition is that found in a closed non-leaky confined aquifer system. In this case, since the concept of perennial usage is not applicable then socio-economic factors must be emphasized and taken into consideration in evaluation of the yield.

(3) Permissive yield

In determining the yield from an aquifer or a groundwater basin, as understood from the above concept and its definition, not only must groundwater be viewed from its natural scientific characteristics, but groudwater resources must also be viewed from a socio-economic perspective. This means that instead of using the term, "safe yield", the above two concepts are grasped and combined to create a term reflecting a more socio-scientific sense, resulting in the term, "permissive yield" (Water Balance Research Group, 1976).

The term"permissive yield" is defined as "the amount of groundwater that the inhabitants consider allowable to withdraw from a perspective of profit/loss in pumping". The combination of important factors for this definition are given in Table 7-1 below.

Table 7-1 Important Factors in Determining Permissive Yield.

permissive yield	sustained (perennial) yield / mining yield
groundwater characteristics	unconfined ←→ confined (shallow) (deep)
velocity of circulation	rapid ←→ slow
renewal	renewal ←→ unrenewal
criteria	hydrological equilibrium / economic risks water rights / deterioration of water quality

The important factor in the determination of permissive yield is the circulation velocity of the groundwater. In other words, the situation depends on whether or not the groundwater is renewable. This disparity is relative, and the hydrologic equilibrium condition is emphasized in the determination of the yield of renewable unconfined groundwater of a comparatively rapid circulation. Contrasting this is unrenewable confined groundwater of a slow circulation. As it approaches a closed state, its mining components harden, which, in turn, greatly influences the socio-economic conditions which are emphasized in the determining of permissible yield.

(4) Concept of yield evaluation for the study area

The potential yield of groundwater in the study area is quite large. However, the condition of the groundwater is rather variable, ranging from unconfined groundwater found in fadama, basement rock weathering zones and Kalambaina limestone to confined groundwater found in the Sokoto sedimentary basin.

At this point, the basin yield will be assessed from natural physical characteristics of the groundwater, such as the hydrogeological conditions of the aquifer and the equilibrium conditions. Though the permissive yield can not determined at present, the yield will be evaluated with possible consideration of the socio-economic framework.

7-2 Water Balance Analysis

Water balance in the aquifer systems and recharge and discharge of the groundwater basin were calculated in order to establish basic data for studying the potential of groundwater development.

7-2-1 Water Balance Equation

Rainfall on the ground flows out through stream, evaporates and/or infiltrates into the ground. Although rain travels these different routes, the quantity of water initially provided by the rain remains constant.

Accordingly, the equations of water balance are expressed by the following

$$P = O + E + W \quad \text{(7-1)}$$

Where,
- P : Precipitation
- O : Surface outflow
- E : Evapotranspiration
- W: Groundwater recharge

This concept is applicable to groundwater systems. In a groundwater system, water is recharged by rainfall infiltration, infiltration from river beds, inflow from upstream of the aquifer, and leakage from other aquifers. Water is discharged as effluence into streams or springs, by abstraction, as downstream through the aquifer, and as leakage. Besides these factors, change in storage must be taken into account in the equation of groundwater balance. The equation of groundwater balance is thus given as :

$$S\,dH/dt = (Q1 - Q2) / F + W \quad \text{(7-2)}$$

Where,	S dH/dt	: Change in groundwater storage
	S	: Storage coefficient (Where unconfined groundwater is concerned, S is equivalent to the specific yield.)
	dH	: Change in water level
	dt	: Time difference
	(Q1-Q2) / F	: Groundwater run-off
	Q1	: Inflow
	Q2	: Outflow
	F	: Area of water balance
	W	: Groundwater recharge

Groundwater inflow (Q1) involves upstream inflow through the aquifer,recharge from the river bed, and leakage from other aquifers. Groundwater outflow (Q2) involves downstream outflow through the aquifer, effluence to streams or springs, groundwater abstraction, and leakage to other aquifers. When shallow groundwater is concerned, water loss to evapotranspiration is involved in groundwater outflow.

7-2-2 Recharge estimation for unconfined aquifers in the sedimentary area

(1) Basic formula for shallow groundwater balance

When surface outflow (O) in Eq. (7-1) is approximated to be proportional to precipitation, water infiltrated into ground (P') becomes approximately as follows :

$$P' = (1-C) * P \quad \text{.................................} \quad (7\text{-}3)$$

Groundwater recharge (W) is estimated from P', E, and water holding capacity of soils (Mdmax) composing the unsaturated zone. The procedure to calculate W is as follows :

P' infiltrates into the ground and increase the water content (Md) in the unsaturated zone. Then Md is decreased by evaportranspiration (E). If the remaining Md surpasses Mdmax, the excess becomes groundwater recharge. These procedures are expressed as:

$$Mdt = Mdt\text{-}1 + P'\text{-}E \quad \text{.............................} \quad (7\text{-}4)$$

$$W = 0 \quad \text{...} \quad (7\text{-}5\text{-}1)$$

$$W = Mdt\text{-}Mdmax \quad (Mdt > Mdmax) \quad \text{.............} \quad (7\text{-}5\text{-}2)$$

$$Mdt = Mdmax \quad Mdt > Mdmax) \quad \text{..............} \quad (7\text{-}5\text{-}3)$$

Where Mdt-1: Water content in the saturated zone in previous time step

Mdt : Water content in the saturated zone in present time step

Considering an ideal unconfined groundwater basin where groundwater inflow and abstraction are neglected, Eq. (7-2) can be expressed as

$$S\, dH/dt = -Q2/F + W \quad \text{........................} \quad (7\text{-}6)$$

In the dry season when the infiltration of precipitation is neglected, Eq. (7-6) becomes

$$S\, dH/dt = -Q2/F \quad \text{.............................} \quad (7\text{-}7)$$

Water level and change in water level in the dry season can be assumed to have the linear relationship as follows

$$dH/dt = a * H + b \quad \text{.............................} \quad (7\text{-}8)$$

Where H : Water level

a, b : Constants

The constants can be determined by analyzing a recession curve of shallow groundwater level in the dry season.
Replacing Eq. (7-7) by Eq. (7-8), we obtain

$$-Q2 = S * F * (a * H + b) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7\text{-}9)$$

If Eq. (7-9) is substituted in Eq. (7-6), then the basic formula for shallow groundwater balance finally becomes

$$S\, dH/dt = S * (a * H + b) + W \quad \ldots\ldots\ldots\ldots\ldots \quad (7\text{-}10)$$

(2) Computation of the recharge analysis

Two places in the sedimentary area were chosen in order to calculate the recharge rate. They are Kware on the Kalambaina formation and Tangaza on the Gwandu formation. Long-term shallow groundwater records obtained by the USGS (1973) are available at both places (Fig. 7-1)

(a) Precipitation and Evapotranspiration

Monthly rainfall records for the Sokoto aerodrome were used for calculation. Difference in precipitation by place was assumed to be negligible. Potential evapotranspiration was estimated by the Thornthwaite empirical formula using meteorological data for the Sokoto aerodrome. Calculated annual potential evapotranspiration for Sokoto was 1695mm in 1964 and 1664m in 1965. Since these values are larger than annual precipitations which were 729mm in 1964 and 974mm in 1965, modification in the course of the water balance analysis was given to determine actual evapotranspiration.

(b) Constants for Eq. (7-8)

The hydrographies for shallow groundwater levels at Kware and Tangaza were used to determine the constants a and b for Eq. (7-8). By substituting five days for dt, the linear relation between (H) and (dH/dt) was recognized, as shown in Fig. 7-2 (1), (2).

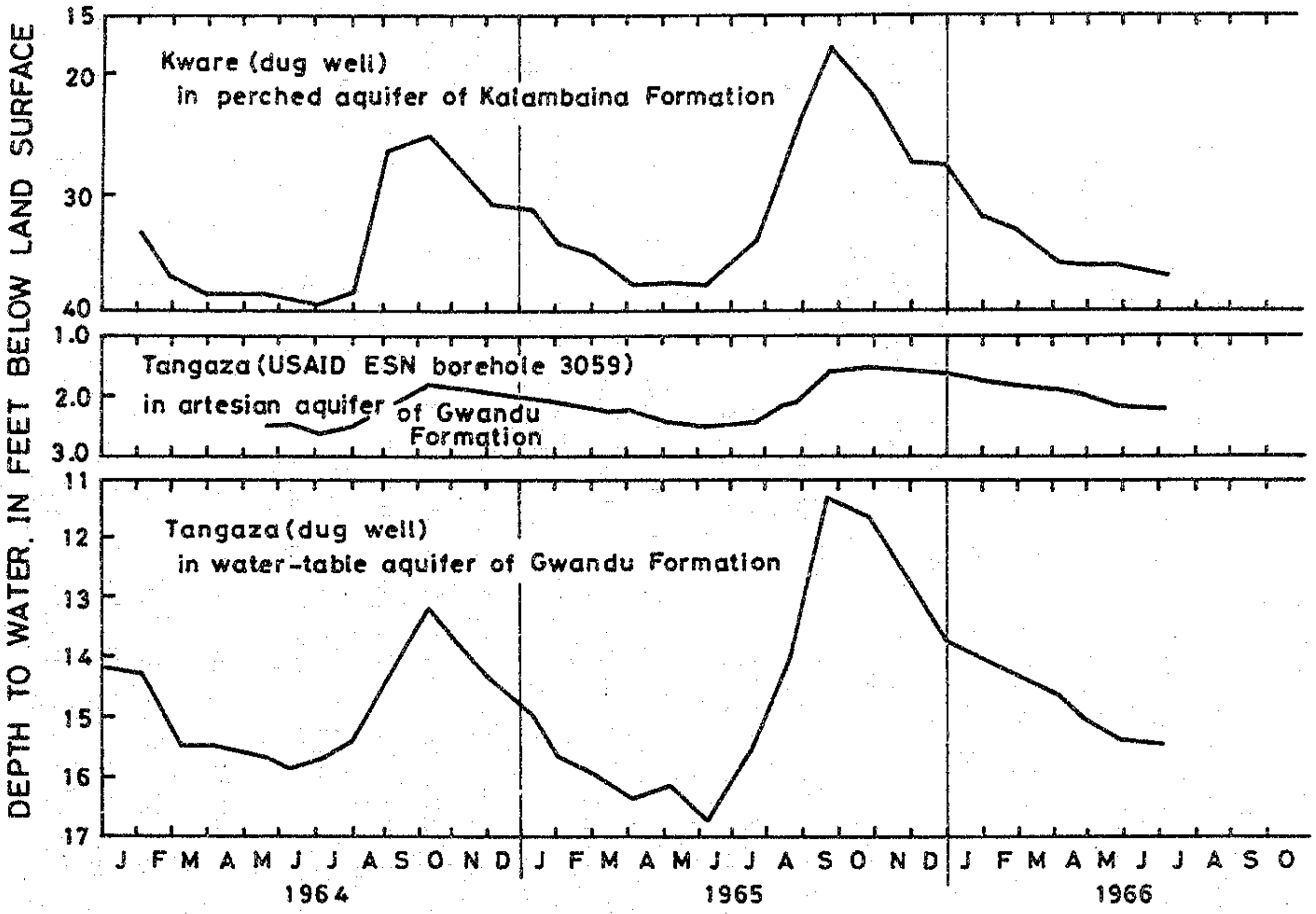


Fig. 7-1 Water-level fluctuations in dug wells tapping unconfined groundwater in Kalambaina and Gwandn Formations

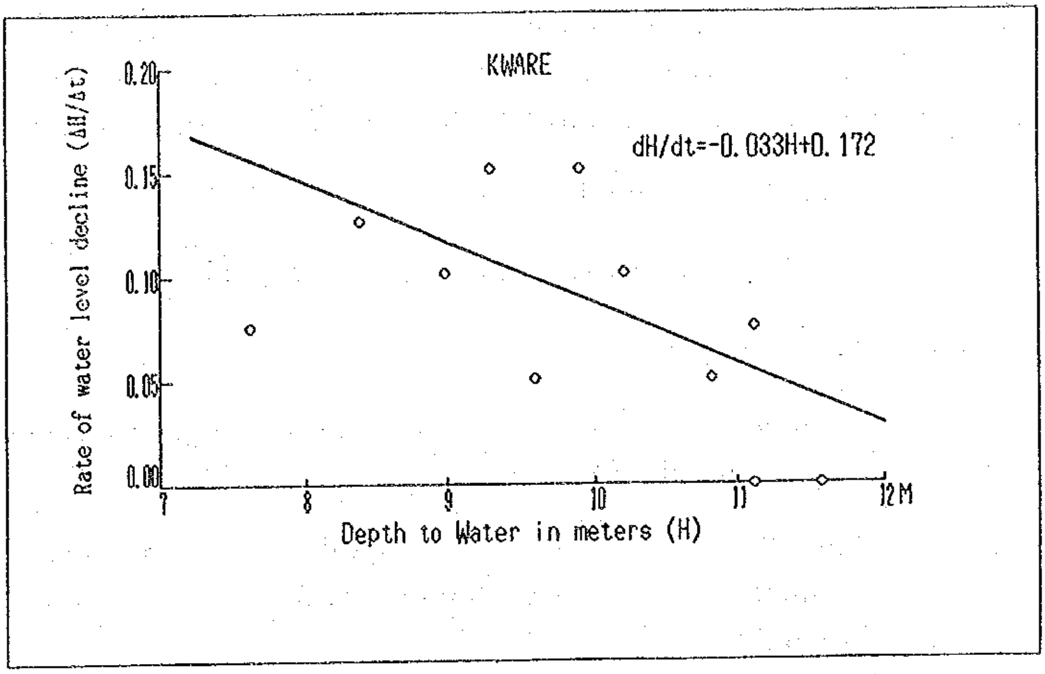


Fig. 7-2 (1) Relation between Groundwater Level and Rate of Decline - Kware -

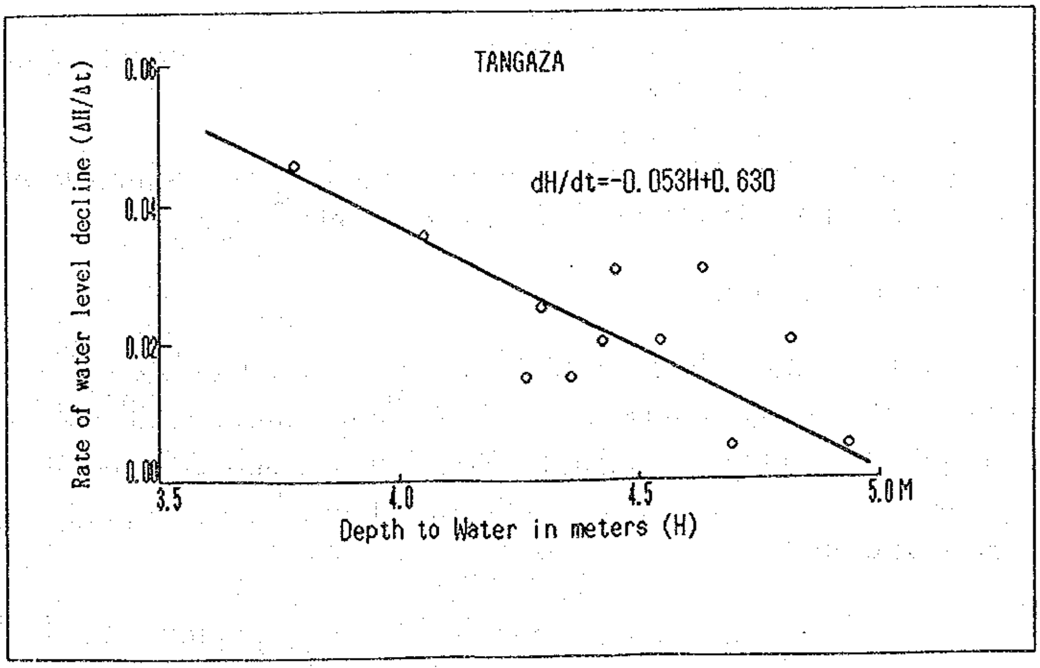


Fig. 7-2 (2) Relation between Groundwater Level and Rate of Decline - Tangaza -

The constants a, b for each groundwater situation were calculated by the least square method. The linear relationships between water level and change in water level for the selected two hydrographies become

Kware $dH/dt = -0.32 * H + 3.78$ (m) .... (7-11-1)

Tangaza $dH/dt = -0.20 * H + 1.03$ (m) .... (7-11-2)

(c) Computation procedure

Water balance calculation based on Eq. (7-3) through Eq. (7-11) was carried out based on the following procedure.

a. Initial water level is chosen from the water level record. Time step one is set. Parameters (S), (C), and (Mdmax) are carefully chosen and given in the equation.

b. P and E at each time step are given to Eq. (7-3) through (7-5) and W is calculated.

c. By giving W to Eq. (7-10), dH/dt is calculated.

d. H of next time step is calculated as $H = H + dH$.

e. If the time step comes to the end, then computation stops, otherwise repeat the procedure from b.

Parameters S, C and Mdmax are changed on a trial and error basis, until the calculated water levels match the actual groundwater levels.

(d) Results of computation

Results of the water balance calculations for shallow groundwater are shown in Tab. 7-2. The comparisons of actual and computed groundwater levels are shown in Fig. 7-3. As shown in the figures, agreement between computed level and actual levels is achieved. Parameters determined in the calculation are :

Tab. 7-2 (1) Water Balance Calculated at Kware
Precipitation, Potential Evapotranspiration : Sokoto

C=0.95 U=0.03 MMAX=50mm KWARE (1964 MAY - 1966 APL)

STEP	MONTH	P	E	P*C	W	ΔH	H	M
0							11734.80	0.00
1	MAY	40.00	29.20	38.00	0.00	4.06	11738.86	8.80
2		0.00	29.20	0.00	0.00	3.85	11742.71	0.00
3		0.00	29.20	0.00	0.00	3.64	11746.35	0.00
4		0.00	29.20	0.00	0.00	3.45	11749.80	0.00
5		0.00	29.20	0.00	0.00	3.26	11753.07	0.00
6		7.00	29.20	6.65	0.00	3.09	11756.16	0.00
7	JUN	17.00	26.36	16.15	0.00	2.93	11759.08	0.00
8		11.00	25.65	10.45	0.00	2.77	11761.85	0.00
9		69.00	25.65	65.55	0.00	2.62	11764.47	39.90
10		17.00	25.65	16.15	0.00	2.48	11766.95	30.40
11		40.00	25.65	38.00	0.00	2.35	11769.30	42.75
12		14.00	25.65	13.30	0.00	2.22	11771.53	30.40
13	JUL	4.00	23.73	3.80	0.00	2.11	11773.63	10.47
14		2.00	23.25	1.90	0.00	1.99	11775.62	0.00
15		29.00	23.25	27.55	0.00	1.89	11777.51	4.30
16		80.00	23.25	76.00	7.05	14.32	11556.83	50.00
17		38.00	23.25	36.10	12.85	36.40	11164.90	50.00
18		43.00	23.25	40.85	17.60	65.75	10643.98	50.00
19	AUG	32.00	20.91	30.40	9.49	79.11	10408.76	50.00
20		11.00	19.35	10.45	0.00	74.89	10481.65	41.10
21		18.00	19.35	17.10	0.00	70.90	10552.55	38.85
22		14.00	19.35	13.30	0.00	67.12	10619.67	32.80
23		19.00	19.35	18.05	0.00	63.54	10683.20	31.50
24		79.00	19.35	75.05	37.20	126.28	9569.49	50.00
25	SEP	12.00	20.61	11.40	0.00	119.55	9689.03	40.79
26		12.00	22.50	11.40	0.00	113.17	9802.21	29.69
27		91.00	22.50	86.45	43.64	184.72	8532.26	50.00
28		7.00	22.50	6.65	0.00	174.87	8707.12	34.15
29		3.00	22.50	2.85	0.00	165.54	8872.66	14.50
30		14.00	22.50	13.30	0.00	156.71	9029.37	5.30
31	OCT	0.00	23.24	0.00	0.00	148.35	9177.73	0.00
32		0.00	24.35	0.00	0.00	140.44	9318.17	0.00
33		0.00	24.35	0.00	0.00	132.95	9451.12	0.00
34		0.00	24.35	0.00	0.00	125.86	9576.98	0.00
35		0.00	24.35	0.00	0.00	119.15	9696.13	0.00
36		0.00	24.35	0.00	0.00	112.79	9808.92	0.00
37	NOV	0.00	23.25	0.00	0.00	106.78	9915.70	0.00
38		0.00	18.85	0.00	0.00	101.08	10016.78	0.00
39		0.00	18.85	0.00	0.00	95.69	10112.47	0.00
40		0.00	18.85	0.00	0.00	90.59	10203.06	0.00
41		0.00	18.85	0.00	0.00	85.76	10288.82	0.00
42		0.00	18.85	0.00	0.00	81.18	10370.00	0.00
43	DES	0.00	18.49	0.00	0.00	76.85	10446.85	0.00
44		0.00	17.05	0.00	0.00	72.75	10519.61	0.00
45		0.00	17.05	0.00	0.00	68.87	10588.48	0.00
46		0.00	17.05	0.00	0.00	65.20	10653.68	0.00
47		0.00	17.05	0.00	0.00	61.72	10715.41	0.00
48		0.00	17.05	0.00	0.00	58.43	10773.84	0.00
49	JAN	0.00	17.05	0.00	0.00	55.32	10829.16	0.00
50		0.00	18.40	0.00	0.00	52.37	10881.52	0.00
51		0.00	18.40	0.00	0.00	49.57	10931.09	0.00
52		0.00	18.40	0.00	0.00	46.93	10978.02	0.00
53		0.00	18.40	0.00	0.00	44.43	11022.45	0.00
54		0.00	18.40	0.00	0.00	42.06	11064.50	0.00
55	FEB	0.00	18.40	0.00	0.00	39.81	11104.32	0.00
56		0.00	22.96	0.00	0.00	37.69	11142.01	0.00
57		0.00	24.10	0.00	0.00	35.68	11177.69	0.00
58		0.00	24.10	0.00	0.00	33.78	11211.46	0.00
59		0.00	24.10	0.00	0.00	31.98	11243.44	0.00
60		0.00	24.10	0.00	0.00	30.27	11273.71	0.00
61	MAR	0.00	24.10	0.00	0.00	28.66	11302.36	0.00
62		0.00	25.90	0.00	0.00	27.13	11329.49	0.00
63		0.00	25.90	0.00	0.00	25.68	11355.17	0.00
64		0.00	25.90	0.00	0.00	24.31	11379.48	0.00
65		0.00	25.90	0.00	0.00	23.01	11402.50	0.00
66		0.00	25.90	0.00	0.00	21.78	11424.28	0.00
67	APL	0.00	25.90	0.00	0.00	20.62	11444.91	0.00
68		0.00	28.06	0.00	0.00	19.52	11464.43	0.00
69		0.00	28.60	0.00	0.00	18.48	11482.92	0.00
70		0.00	28.60	0.00	0.00	17.50	11500.42	0.00
71		0.00	28.60	0.00	0.00	16.56	11516.98	0.00
72		0.00	28.60	0.00	0.00	15.68	11532.66	0.00

Unit P, E : mm/5days, ΔH : mm/5days, H : GL-mm

Tab. 7-2 (2) Water Balance Calculated at Kware
Precipitation, Potential Evapotranspiration : Sokoto

C=0.95 U=0.16 HMAX=50mm TANGAZA (1964 MAY - 1968 APL)

STEP	MONTH	P	E	P*C	W	ΔH	H	M
73	MAY	0.00	28.60	0.00	0.00	14.84	11547.50	0.00
74		0.00	29.36	0.00	0.00	14.05	11561.56	0.00
75		0.00	29.55	0.00	0.00	13.30	11574.86	0.00
76		0.00	29.55	0.00	0.00	12.59	11587.46	0.00
77		0.00	29.55	0.00	0.00	11.92	11599.38	0.00
78		0.00	29.55	0.00	0.00	11.29	11610.66	0.00
79	JUN	45.00	29.55	42.75	0.00	10.68	11621.35	13.20
80		0.00	27.00	0.00	0.00	10.11	11631.46	0.00
81		100.00	25.30	95.00	19.70	44.60	11019.39	50.00
82		85.00	25.30	80.75	55.45	140.80	9311.86	50.00
83		21.00	25.30	19.95	0.00	133.29	9445.15	44.65
84		13.00	25.30	12.35	0.00	126.18	9571.32	31.70
85	JUL	5.00	25.30	4.75	0.00	119.45	9690.77	11.15
86		60.00	24.31	57.00	0.00	113.08	9803.85	43.84
87		0.00	23.65	0.00	0.00	107.05	9910.90	20.19
88		12.00	23.65	11.40	0.00	101.34	10012.24	7.94
89		0.00	23.65	0.00	0.00	95.93	10108.17	0.00
90		21.00	23.65	19.95	0.00	90.82	10198.99	0.00
91	AUG	92.00	23.65	87.40	13.75	110.42	9851.08	50.00
92		28.00	22.03	26.60	4.57	112.65	9811.40	50.00
93		80.00	19.60	76.00	56.40	206.91	8138.31	50.00
94		87.00	19.60	82.65	63.05	307.97	6344.61	50.00
95		35.00	19.60	33.25	13.65	315.81	6205.41	50.00
96		31.00	19.60	29.45	9.85	316.48	6193.56	50.00
97	SEP	10.00	19.60	9.50	0.00	299.60	6493.15	39.90
98		81.00	20.04	76.95	46.81	366.84	5299.66	50.00
99		94.00	21.80	89.30	67.50	467.27	3516.93	50.00
100		22.00	21.80	20.90	0.00	442.35	3959.28	49.10
101		39.00	21.80	37.05	14.35	444.27	3925.22	50.00
102		0.00	21.80	0.00	0.00	420.58	4345.79	28.20
103	OCT	4.00	21.80	3.80	0.00	398.14	4743.94	10.20
104		8.00	22.44	7.60	0.00	376.91	5120.85	0.00
105		5.00	25.00	4.75	0.00	356.81	5477.65	0.00
106		0.00	25.00	0.00	0.00	337.78	5815.43	0.00
107		0.00	25.00	0.00	0.00	319.76	6135.20	0.00
108		0.00	25.00	0.00	0.00	302.71	6437.90	0.00
109	NOV	0.00	25.00	0.00	0.00	286.57	6724.47	0.00
110		0.00	25.00	0.00	0.00	271.28	6995.75	0.00
111		0.00	16.50	0.00	0.00	256.81	7252.56	0.00
112		0.00	16.50	0.00	0.00	243.12	7495.68	0.00
113		0.00	16.50	0.00	0.00	230.15	7725.83	0.00
114		0.00	16.50	0.00	0.00	217.88	7943.71	0.00
115	DES	0.00	16.50	0.00	0.00	206.26	8149.96	0.00
116		0.00	16.50	0.00	0.00	195.26	8345.22	0.00
117		0.00	10.45	0.00	0.00	184.84	8530.06	0.00
118		0.00	10.45	0.00	0.00	174.98	8705.04	0.00
119		0.00	10.45	0.00	0.00	165.65	8870.70	0.00
120		0.00	10.45	0.00	0.00	156.82	9027.51	0.00
121	JAN	0.00	10.45	0.00	0.00	148.45	9175.96	0.00
122		0.00	10.45	0.00	0.00	140.54	9316.50	0.00
123		0.00	16.81	0.00	0.00	133.04	9449.54	0.00
124		0.00	18.40	0.00	0.00	125.94	9575.48	0.00
125		0.00	18.40	0.00	0.00	119.23	9694.71	0.00
126		0.00	18.40	0.00	0.00	112.87	9807.58	0.00
127	FEB	0.00	18.40	0.00	0.00	106.85	9914.43	0.00
128		0.00	18.40	0.00	0.00	101.15	10015.58	0.00
129		0.00	21.82	0.00	0.00	95.76	10111.34	0.00
130		0.00	24.10	0.00	0.00	90.65	10201.98	0.00
131		0.00	24.10	0.00	0.00	85.81	10287.80	0.00
132		0.00	24.10	0.00	0.00	81.24	10369.04	0.00
133	MAR	0.00	24.10	0.00	0.00	76.90	10445.94	0.00
134		0.00	24.10	0.00	0.00	72.80	10518.74	0.00
135		0.00	25.54	0.00	0.00	68.92	10587.66	0.00
136		0.00	25.90	0.00	0.00	65.24	10652.91	0.00
137		0.00	25.90	0.00	0.00	61.76	10714.67	0.00
138		0.00	25.90	0.00	0.00	58.47	10773.14	0.00
139	APL	0.00	25.90	0.00	0.00	55.35	10828.50	0.00
140		0.00	25.90	0.00	0.00	52.40	10880.90	0.00
141		0.00	27.52	0.00	0.00	49.61	10930.50	0.00
142		8.00	28.60	7.60	0.00	46.96	10977.46	0.00
143		0.00	28.60	0.00	0.00	44.46	11021.92	0.00
144		4.00	28.60	3.80	0.00	42.08	11064.00	0.00

Unit P, E : mm/5days, ΔH : mm/5days, H : GL-mm

Tab. 7-2 (3) Water Balance Calculated at Kware
Precipitation, Potential Evapotranspiration : Sokoto

C=0.95 U=0.16 MMAX=50mm TANGAZA (1964 MAY - 1966 APL)

STEP	MONTH	P	E	P*C	W	ΔH	H	M
0							4754.88	0.00
1	MAY	40.00	29.20	38.00	0.00	13.21	4768.09	8.80
2		0.00	29.20	0.00	0.00	12.77	4780.86	0.00
3		0.00	29.20	0.00	0.00	12.34	4793.20	0.00
4		0.00	29.20	0.00	0.00	11.93	4805.13	0.00
5		0.00	29.20	0.00	0.00	11.53	4816.66	0.00
6		7.00	29.20	6.65	0.00	11.15	4827.81	0.00
7	JUN	17.00	26.36	16.15	0.00	10.78	4838.59	0.00
8		11.00	25.65	10.45	0.00	10.42	4849.00	0.00
9		69.00	25.65	65.55	0.00	10.07	4859.08	39.90
10		17.00	25.65	16.15	0.00	9.73	4868.81	30.40
11		40.00	25.65	38.00	0.00	9.41	4878.22	42.75
12		14.00	25.65	13.30	0.00	9.10	4887.32	30.40
13	JUL	4.00	23.73	3.80	0.00	8.79	4896.11	10.47
14		2.00	23.25	1.90	0.00	8.50	4904.61	0.00
15		29.00	23.25	27.55	0.00	8.22	4912.83	4.30
16		80.00	23.25	76.00	7.05	9.41	4878.18	50.00
17		38.00	23.25	36.10	12.85	11.78	4809.64	50.00
18		43.00	23.25	40.85	17.60	15.05	4714.69	50.00
19	AUG	32.00	20.91	30.40	9.49	16.52	4671.90	50.00
20		11.00	19.35	10.45	0.00	15.97	4687.88	41.10
21		18.00	19.35	17.10	0.00	15.44	4703.32	38.85
22		14.00	19.35	13.30	0.00	14.93	4718.24	32.80
23		19.00	19.35	18.05	0.00	14.43	4732.67	31.50
24		79.00	19.35	75.05	37.20	21.70	4521.87	50.00
25	SEP	12.00	20.61	11.40	0.00	20.97	4542.85	40.79
26		12.00	22.50	11.40	0.00	20.28	4563.12	29.69
27		91.00	22.50	86.45	43.64	28.69	4319.06	50.00
28		7.00	22.50	6.65	0.00	27.74	4346.80	34.15
29		3.00	22.50	2.85	0.00	26.81	4373.61	14.50
30		14.00	22.50	13.30	0.00	25.92	4399.53	5.30
31	OCT	0.00	23.24	0.00	0.00	25.05	4424.58	0.00
32		0.00	24.35	0.00	0.00	24.22	4448.80	0.00
33		0.00	24.35	0.00	0.00	23.41	4472.21	0.00
34		0.00	24.35	0.00	0.00	22.63	4494.84	0.00
35		0.00	24.35	0.00	0.00	21.88	4516.71	0.00
36		0.00	24.35	0.00	0.00	21.15	4537.86	0.00
37	NOV	0.00	23.25	0.00	0.00	20.44	4558.30	0.00
38		0.00	18.85	0.00	0.00	19.76	4578.06	0.00
39		0.00	18.85	0.00	0.00	19.10	4597.17	0.00
40		0.00	18.85	0.00	0.00	18.47	4615.63	0.00
41		0.00	18.85	0.00	0.00	17.85	4633.48	0.00
42		0.00	18.85	0.00	0.00	17.25	4650.74	0.00
43	DES	0.00	18.49	0.00	0.00	16.68	4667.42	0.00
44		0.00	17.05	0.00	0.00	16.12	4683.54	0.00
45		0.00	17.05	0.00	0.00	15.59	4699.12	0.00
46		0.00	17.05	0.00	0.00	15.07	4714.19	0.00
47		0.00	17.05	0.00	0.00	14.56	4728.76	0.00
48		0.00	17.05	0.00	0.00	14.08	4742.83	0.00
49	JAN	0.00	17.05	0.00	0.00	13.61	4756.44	0.00
50		0.00	18.40	0.00	0.00	13.16	4769.60	0.00
51		0.00	18.40	0.00	0.00	12.72	4782.32	0.00
52		0.00	18.40	0.00	0.00	12.29	4794.61	0.00
53		0.00	18.40	0.00	0.00	11.88	4806.49	0.00
54		0.00	18.40	0.00	0.00	11.49	4817.98	0.00
55	FEB	0.00	18.40	0.00	0.00	11.10	4829.09	0.00
56		0.00	22.96	0.00	0.00	10.73	4839.82	0.00
57		0.00	24.10	0.00	0.00	10.38	4850.20	0.00
58		0.00	24.10	0.00	0.00	10.03	4860.23	0.00
59		0.00	24.10	0.00	0.00	9.70	4869.92	0.00
60		0.00	24.10	0.00	0.00	9.37	4879.30	0.00
61	MAR	0.00	24.10	0.00	0.00	9.06	4888.36	0.00
62		0.00	25.90	0.00	0.00	8.76	4897.12	0.00
63		0.00	25.90	0.00	0.00	8.47	4905.58	0.00
64		0.00	25.90	0.00	0.00	8.18	4913.77	0.00
65		0.00	25.90	0.00	0.00	7.91	4921.68	0.00
66		0.00	25.90	0.00	0.00	7.65	4929.33	0.00
67	APL	0.00	25.90	0.00	0.00	7.39	4936.72	0.00
68		0.00	28.06	0.00	0.00	7.15	4943.87	0.00
69		0.00	28.60	0.00	0.00	6.91	4950.77	0.00
70		0.00	28.60	0.00	0.00	6.68	4957.45	0.00
71		0.00	28.60	0.00	0.00	6.46	4963.91	0.00
72		0.00	28.60	0.00	0.00	6.24	4970.15	0.00

Unit P,E : mm/5days, ΔH : mm/5days, H : GL-mm

Tab. 7-2 (4) Water Balance Calculated at Kwáre
Precipitation, Potential Evapotranspiration : Sokoto

C=0.95 U=0.03 MMAX=50mm KWARE (1964 MAY - 1968 APL)

STEP	MONTH	P	E	P*C	W	ΔH	H	M
73	MAY	0.00	28.60	0.00	0.00	6.03	4976.18	0.00
74		0.00	29.36	0.00	0.00	5.83	4982.01	0.00
75		0.00	29.55	0.00	0.00	5.64	4987.65	0.00
76		0.00	29.55	0.00	0.00	5.45	4993.10	0.00
77		0.00	29.55	0.00	0.00	5.27	4998.37	0.00
78		0.00	29.55	0.00	0.00	5.09	5003.46	0.00
79	JUN	45.00	29.55	42.75	0.00	4.92	5008.38	13.20
80		0.00	27.00	0.00	0.00	4.76	5013.14	0.00
81		100.00	25.30	95.00	19.70	8.70	4898.72	50.00
82		85.00	25.30	80.75	55.45	19.97	4572.12	50.00
83		21.00	25.30	19.95	0.00	19.30	4591.42	44.65
84		13.00	25.30	12.35	0.00	18.66	4610.08	31.70
85	JUL	5.00	25.30	4.75	0.00	18.03	4628.11	11.15
86		60.00	24.31	57.00	0.00	17.43	4645.54	43.84
87		0.00	23.65	0.00	0.00	16.85	4662.40	20.19
88		12.00	23.65	11.40	0.00	16.29	4678.69	7.94
89		0.00	23.65	0.00	0.00	15.75	4694.43	0.00
90		21.00	23.65	19.95	0.00	15.22	4709.66	0.00
91	AUG	92.00	23.65	87.40	13.75	17.58	4641.30	50.00
92		28.00	22.03	26.60	4.57	17.95	4630.68	50.00
93		80.00	19.60	76.00	56.40	29.10	4307.28	50.00
94		87.00	19.60	82.65	63.05	41.26	3954.48	50.00
95		35.00	19.60	33.25	13.65	42.73	3911.90	50.00
96		31.00	19.60	29.45	9.85	43.36	3893.70	50.00
97	SEP	10.00	19.60	9.50	0.00	41.91	3935.61	39.90
98		81.00	20.04	76.95	46.81	50.27	3693.32	50.00
99		94.00	21.80	89.30	67.50	62.66	3334.10	50.00
100		22.00	21.80	20.90	0.00	60.57	3394.67	49.10
101		39.00	21.80	37.05	14.35	61.54	3366.52	50.00
102		0.00	21.80	0.00	0.00	59.49	3426.00	28.20
103	OCT	4.00	21.80	3.80	0.00	57.50	3483.51	10.20
104		8.00	22.44	7.60	0.00	55.59	3539.10	0.00
105		5.00	25.00	4.75	0.00	53.73	3592.83	0.00
106		0.00	25.00	0.00	0.00	51.94	3644.77	0.00
107		0.00	25.00	0.00	0.00	50.21	3694.98	0.00
108		0.00	25.00	0.00	0.00	48.54	3743.52	0.00
109	NOV	0.00	25.00	0.00	0.00	46.92	3790.44	0.00
110		0.00	25.00	0.00	0.00	45.36	3835.80	0.00
111		0.00	16.50	0.00	0.00	43.84	3879.64	0.00
112		0.00	16.50	0.00	0.00	42.38	3922.02	0.00
113		0.00	16.50	0.00	0.00	40.97	3962.99	0.00
114		0.00	16.50	0.00	0.00	39.60	4002.60	0.00
115	DES	0.00	16.50	0.00	0.00	38.28	4040.88	0.00
116		0.00	16.50	0.00	0.00	37.01	4077.89	0.00
117		0.00	10.45	0.00	0.00	35.77	4113.66	0.00
118		0.00	10.45	0.00	0.00	34.58	4148.25	0.00
119		0.00	10.45	0.00	0.00	33.43	4181.68	0.00
120		0.00	10.45	0.00	0.00	32.31	4213.99	0.00
121	JAN	0.00	10.45	0.00	0.00	31.24	4245.23	0.00
122		0.00	10.45	0.00	0.00	30.20	4275.42	0.00
123		0.00	16.81	0.00	0.00	29.19	4304.61	0.00
124		0.00	18.40	0.00	0.00	28.22	4332.83	0.00
125		0.00	18.40	0.00	0.00	27.28	4360.11	0.00
126		0.00	18.40	0.00	0.00	26.37	4386.48	0.00
127	FEB	0.00	18.40	0.00	0.00	25.49	4411.96	0.00
128		0.00	18.40	0.00	0.00	24.64	4436.60	0.00
129		0.00	21.82	0.00	0.00	23.82	4460.42	0.00
130		0.00	24.10	0.00	0.00	23.02	4483.44	0.00
131		0.00	24.10	0.00	0.00	22.26	4505.70	0.00
132		0.00	24.10	0.00	0.00	21.51	4527.21	0.00
133	MAR	0.00	24.10	0.00	0.00	20.80	4548.01	0.00
134		0.00	24.10	0.00	0.00	20.10	4568.11	0.00
135		0.00	25.54	0.00	0.00	19.43	4587.55	0.00
136		0.00	25.90	0.00	0.00	18.79	4606.33	0.00
137		0.00	25.90	0.00	0.00	18.16	4624.49	0.00
138		0.00	25.90	0.00	0.00	17.55	4642.05	0.00
139	APL	0.00	25.90	0.00	0.00	16.97	4659.02	0.00
140		0.00	25.90	0.00	0.00	16.40	4675.42	0.00
141		0.00	27.52	0.00	0.00	15.86	4691.28	0.00
142		8.00	28.60	7.60	0.00	15.33	4706.60	0.00
143		0.00	28.60	0.00	0.00	14.82	4721.42	0.00
144		4.00	28.60	3.80	0.00	14.32	4735.74	0.00

Unit P, E : mm/5days, ΔH : mm/5days, H : GL-mm

Fig. 7-3 (1) Comparison of Computed and Actual Water Level
- Kware -

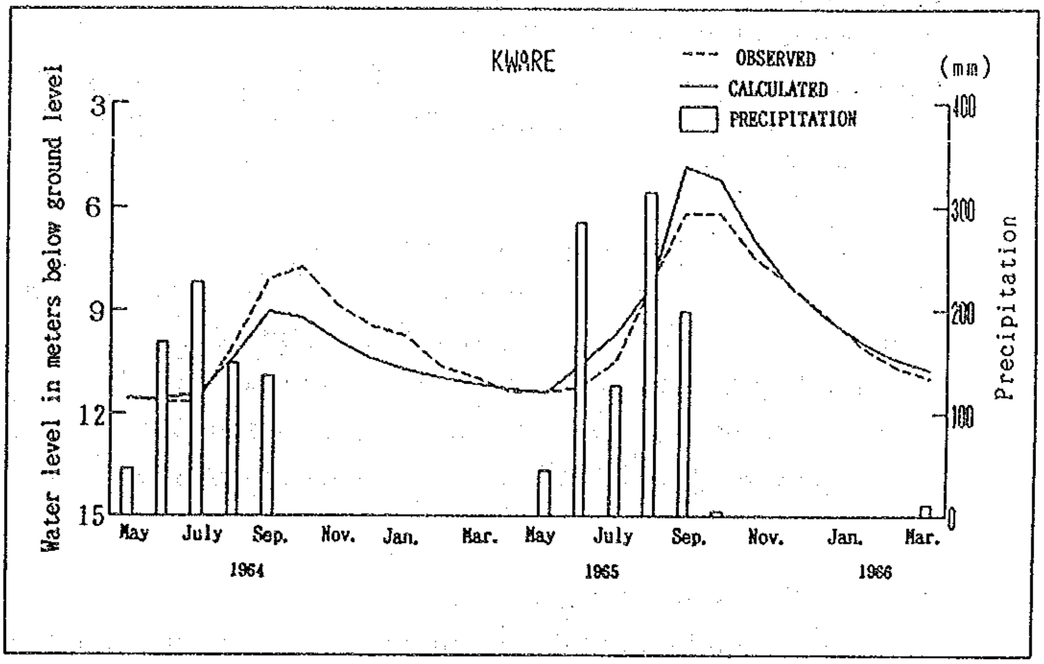
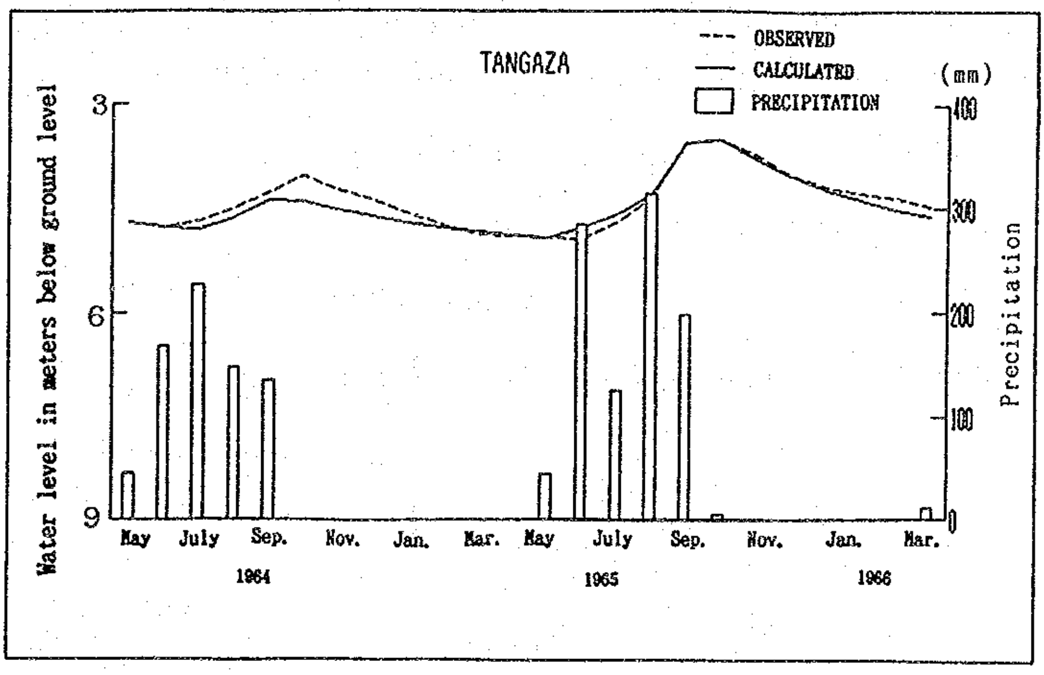


Fig. 7-3 (2) Comparison of Computed and Actual Water Level
- Tangaza -



a. Storage coefficient (S)
   Sediment of aquifer for the Kware shallow well is limestone. That for the Tangaza shallow well is sand.
   Determined S for Kware and Tangaza is 2.5% and 16%, respectively. These values are within the range of the typical specific yield (Tab. 7-3) for sand and limestone.

b. Constant to determine overflow to streams (C)
   C is determined to be 0.05. Since the run-off rations determined from discharge records for the Rima River and Sokoto River are in the range 4-7% (See. 3-4), except for that of Gusau, which is located in the basement complex area, it is reasonable to assume that 5% of the precipitation for the area of the water balance analysis is lost to overflow.

c. Water holding capacity of soil (Mdmax)
   Mdmax is determined as 50 mm. Since no record on the value was available for the area, Mdmax was determined so that other parameters became within reasonable range.

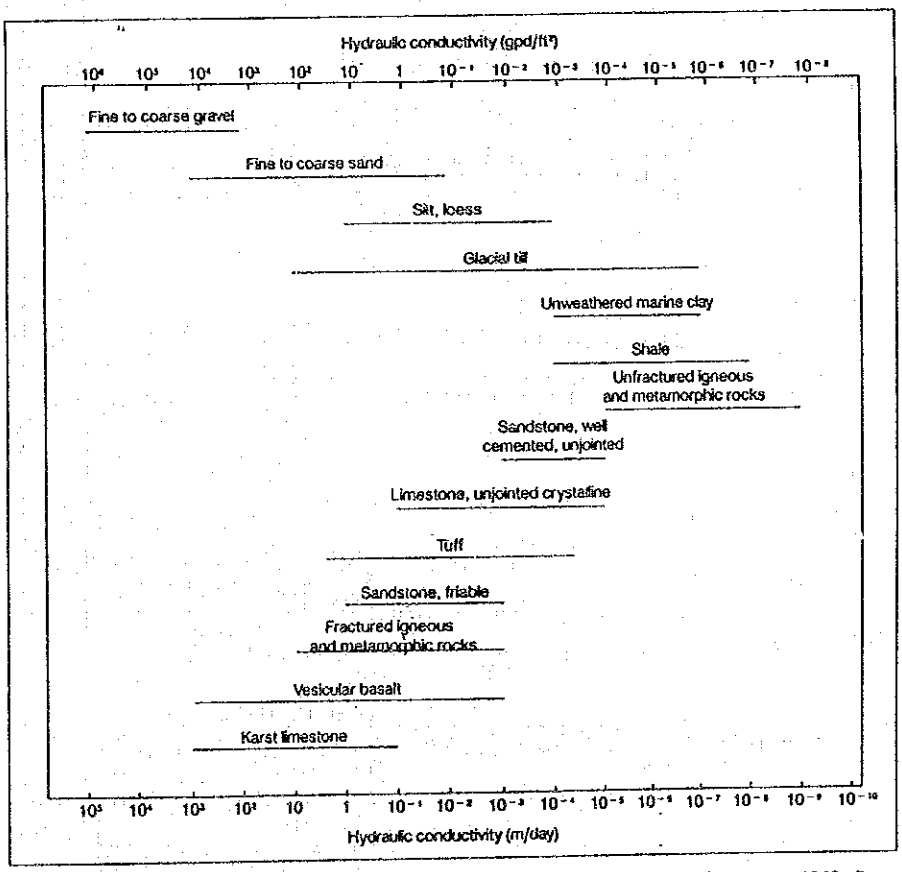
The estimated water balance, by applying the analysis to the precipitations and potential evapotranspirations from 1943 to 1981 for the Sokoto aerodrome, is shown in Tab. 7-4. The calculation was applied to the years which had complete data on daily precipitation and monthly temperature. Average water balance during the period becomes as followings.

Precipitation	674mm (100%)
Surface out flow	34mm (5%)
Evapotranspiration	523mm (78%)
Groundwater recharge	117mm (17%)

Tab. 7-3 Representative Specific Yield Ranges

Sediment	Specific Yield, %
Clay	1–10
Sand	10–30
Gravel	15–30
Sand and Gravel	15–25
Sandstone	5–15
Shale	0.5–5
Limestone	0.5–5

(Walton, 1970)



Typical *K* values for consolidated and unconsolidated aquifers. *(After Davis, 1969; Dunn and Leopold, 1978; Freeze and Cherry, 1979).*

Tab. 7 - 4 Groundwater Recharge computed at Sokoto

P: Precipitation O: Out flow

E: Evapotranspiration W: Groundwater recharge

Year	P	O	E	W
1955	709	35.45	587.00	86.55
1956	704	35.20	435.97	232.83
1957	882	44.10	654.49	183.41
1958	892	44.60	612.74	234.66
1959	562	28.10	392.44	141.46
1960	878	43.90	560.78	273.32
1961	641	32.05	503.50	105.45
1962	675	33.75	534.84	106.41
1963	797	39.85	651.94	105.21
1964	727	36.35	565.52	125.13
1965	978	48.90	560.70	368.40
1967	591	29.55	495.63	65.82
1968	493	24.65	468.35	0.00
1969	483	24.15	417.10	41.75
1971	549	27.45	519.74	1.81
1972	390	19.50	370.50	0.00
1973	560	28.00	517.76	14.24
1975	874	43.70	682.13	148.17
1976	812	40.60	575.42	195.98
1977	690	34.50	514.44	141.06
1978	600	30.00	491.42	78.58
1979	561	28.05	532.95	0.00
1980	555	27.75	499.24	28.01
1981	567	28.35	410.07	128.58
AVE.	674	33.69	523.11	116.95

Unit: mm

7-2-3 Recharge estimation for unconfined aquifers in the basement complex area

The procedure to estimate groundwater recharge for the sedimentary area is assumed to be applicable for the basement complex area. Since no long-term record for unconfined groundwater fluctuation in the area is available, verification for the availability of the results of calculation was not made.

(1) Conditions for computation

The Gusau area was chosen as a model area to calculate water balance in the basement complex area. Considering the aspects of the area, the following conditions for computation were taken.

(a) Precipitation and evapotranspiration

Precipitation records from the Gusau aerodrome were used for the calculation. Potential evapotranspiration determined by the Thornthwaite method, based on the temperature records from the Gusau aerodrome was also used .

(b) Parameters for the calculation

Since the run-off coefficient calculated from the discharge and precipitation records from Gusau is 16.5%, a C determined to be 0.17. Mdmax of 50 mm was applied.

(2) Results of computation

The estimated water balance,by applying the analysis to the precipitations and potential evapotranspirations from 1953 to 1985 for the Gusau aerodrome, is shown in Tab. 7-5. The average water balance during the period becomes as follows :

Precipitation	857mm	(100%)
Surface out flow	146mm	(17%)
Evapotranspiration	576mm	(67%)
Groundwater recharge	135mm	(16%)

Tab. 7 - 5 Groundwater Recharge computed at Gusau

P: Precipitation O: Out flow

E: Evapotranspiration W: Groundwater recharge

Year	P	O	E	W
1963	1125	191.25	721.49	212.26
1964	904	153.68	587.34	162.98
1965	826	140.42	584.34	101.24
1967	913	155.21	529.35	228.44
1968	1021	173.57	716.83	130.60
1969	935	158.95	643.04	133.01
1970	838	142.46	500.21	195.33
1971	811	137.87	492.44	180.69
1972	746	126.82	617.54	1.64
1973	726	123.42	492.22	110.36
1974	857	145.69	532.03	179.28
1977	769	130.73	538.34	99.93
1978	1015	172.55	659.10	183.35
1980	897	152.49	600.63	143.88
1981	787	133.79	571.67	81.54
1982	722	122.74	538.16	61.10
1983	848	144.16	471.28	232.56
1984	679	115.43	525.25	38.32
1985	860	146.20	619.40	94.40
AVE.	857	145.65	575.82	135.31

Unit: mm

7-2-4 Recharge volume

Groundwater recharge rates for the sedimentary area and the basement complex area were estimated as

Sedimentary area	17%
Basement complex area	16%

Fig. 7-4 shows the area of the sedimentary rock and the basement rock together with the isolines of the mean annual rainfall.

The total area of the sedimentary area in Sokoto State is about 60,000 km^2, and that of the basement complex area is about 40,000km^2.

By applying recharge rate of 28% to the sedimentary area and one of 21% to the basement complex area, we obtained recharge volumes as follows :

a. Sedimentary area (60,000 km^2)

(550 mm/year $\times$ 5900 km^2 + 650 $\times$ 13600 + 750 $\times$ 12800 + 850 $\times$ 27700) $\times$ 0.17 $\div$ 1000

= 7689 million cubic meters/year
(128 mm/year)

b. Basement complex area (40,000 km^2)

750 mm/year $\times$ 1900 km^2 + 850 $\times$ 6900 + 950 $\times$ 15800 + 1050 $\times$ 15400) $\times$ 0.16 $\div$ 1000

= 6155 million cubic meters/year
(154 mm/year)

It must be noted that these values are not directly equivalent to recharge volumes for the main aquifers for the areas ; the confined aquifers in the sedimentary area, and the deep weathering zones in the basement complex area. Most of the water stored in the shallow aquifers is probably lost to the evapotranspiration and effluence to streams in the dry season.

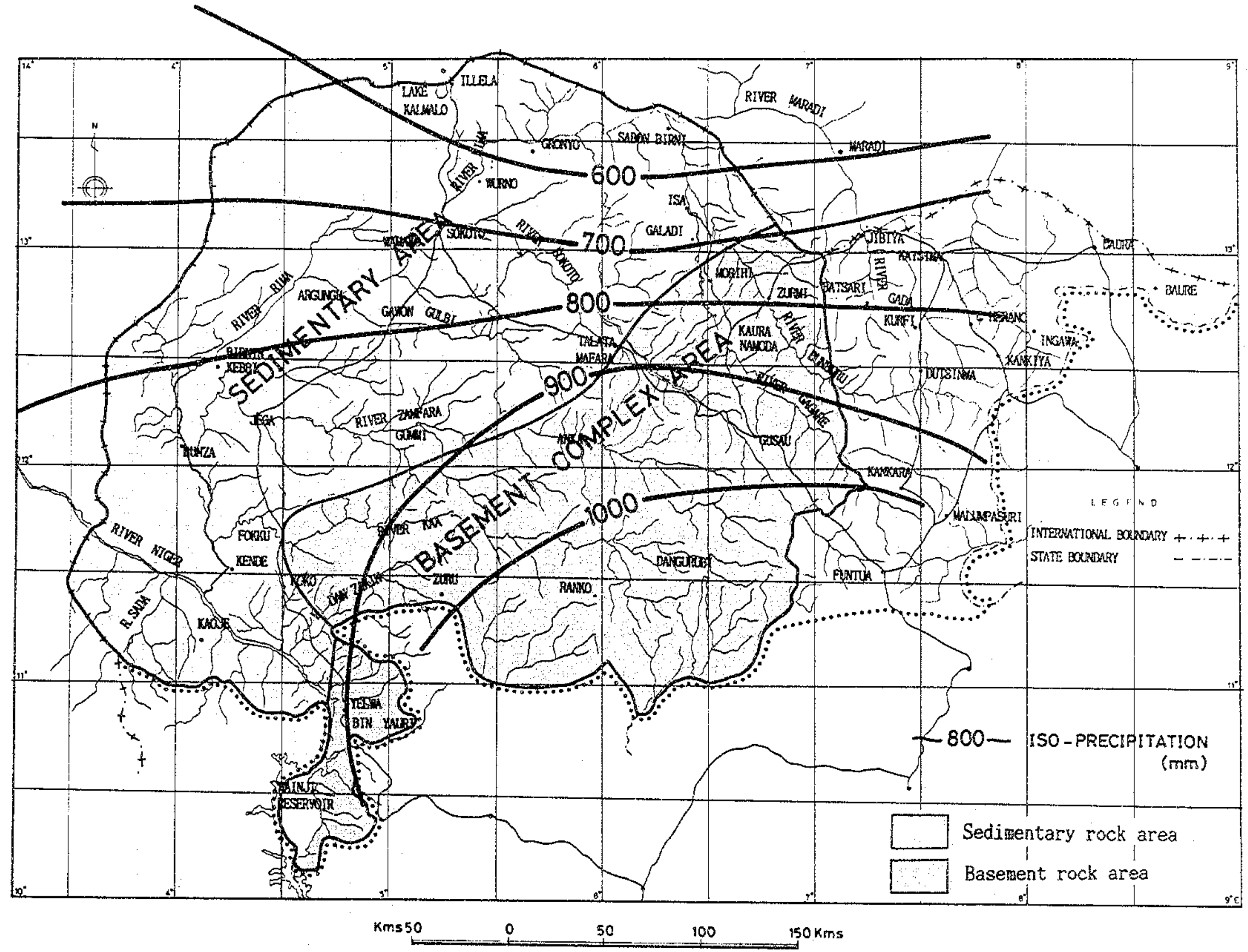


Fig. 7-4 Areas of the Sedimentary Rock and the Basement Rock with the Isoline of Annual Precipitation

Therefore,the recharge volume estimated above should be treated as the retained volume of water in the rainy season. The actual volume of water recharged into the main aquifers is probably several times smaller than the calculated volumes.

7-3 Groundwater Simulation in the Sokoto Groundwater Basin

A numerical model to simulate groundwater movement in the sedimentary area was constructed. Future groundwater movement was predicted by applying future changes in groundwater abstraction.

The simulation technique is described in detail in the Supplementary Report 2.

7-3-1 Groundwater simulation procedure

The procedure for the groundwater simulation is described in Fig. 7-5.

a. The integrated system of the groundwater basin is comprised of area units and aquifer system units referred to as subsystems. A subsystem is further divided into elements (aquifer constants). The scale and accuracy of these elements are subject to the purpose and complexity of the system.

b. The interrelated nature of the subsystems and elements allows quantification of the groundwater simulation model once the program has been written.

c. Initial boundary conditions, as well as historical data (e.g. pumping rates), are incorporated into the model. It is then checked to see whether it represents the actual conditions of groundwater. Through this process, boundary conditions and given parameters are identified.

d. By applying future possible pumping schemes to the calibrated (identified) model, decline in groundwater levels is predicted.

7-3-2 Modeling of the sedimentary rock area

(1) Quasi 3-D model

The digital model used for this study was prepared by Fujisaki, Oka and Kamata (1979). The basic concept is that water in the main aquifers in the

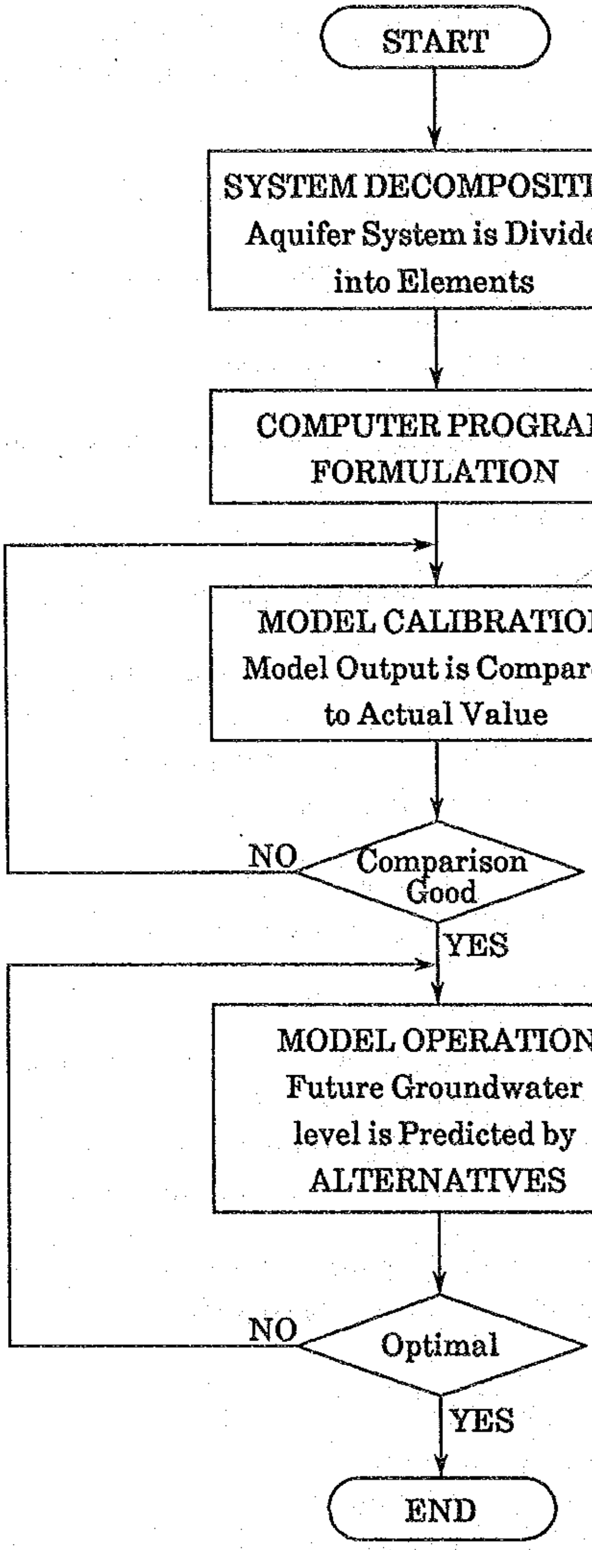


Fig.7-5 General Procedure of Simulation

sedimentary rock area, which are the Gwandu, Kalambaina, Rima and Gundumi aquifers, is supplied by lateral flow through the aquifers and by vertical flow through the aquitards from overlying and underlying aquifers.

A generalized cross-section of a multiple-leakey aquifer system is illustrated in Fig. 7-6. Since vertical and horizontal flow components in the aquitard are ignored in this model, the model is called a quasi 3-D aquifer model. Numerical solutions can be obtained by applying the finite element method (FEM).

(2) Grid design and boundary conditions

The model was applied to the demarcated area as shown in Fig. 7-7. The area has 32 by 27 grid elements. The grid size is 13.5 km by 13.75km. Each grid is provided with code labels to specify hydrogeological boundaries.

The north and west boundaries of the simulation area were modeled as impermeable boundaries, because groundwater flow through the boundaries can be presumed to be negligible by the fact that direction of groundwater flow presumed from the water level configuration maps (Fig. 4-13) is almost parallel to the boundaries.

The east boundaries of the simulation area were modeled as impermeable boundaries, because the boundaries coincide with the outcrop area of the basement complex area. Rocks composing the basement complex area have generally poor permeability compared with those of the sedimentary area, so that groundwater flow between the sedimentary area and the basement complex area can be practically negligible.

The southern boundaries along the River Niger were modeled as constant head boundaries. Groundwater levels along the boundaries are assumed to be equivalent to the water levels in the River Niger.

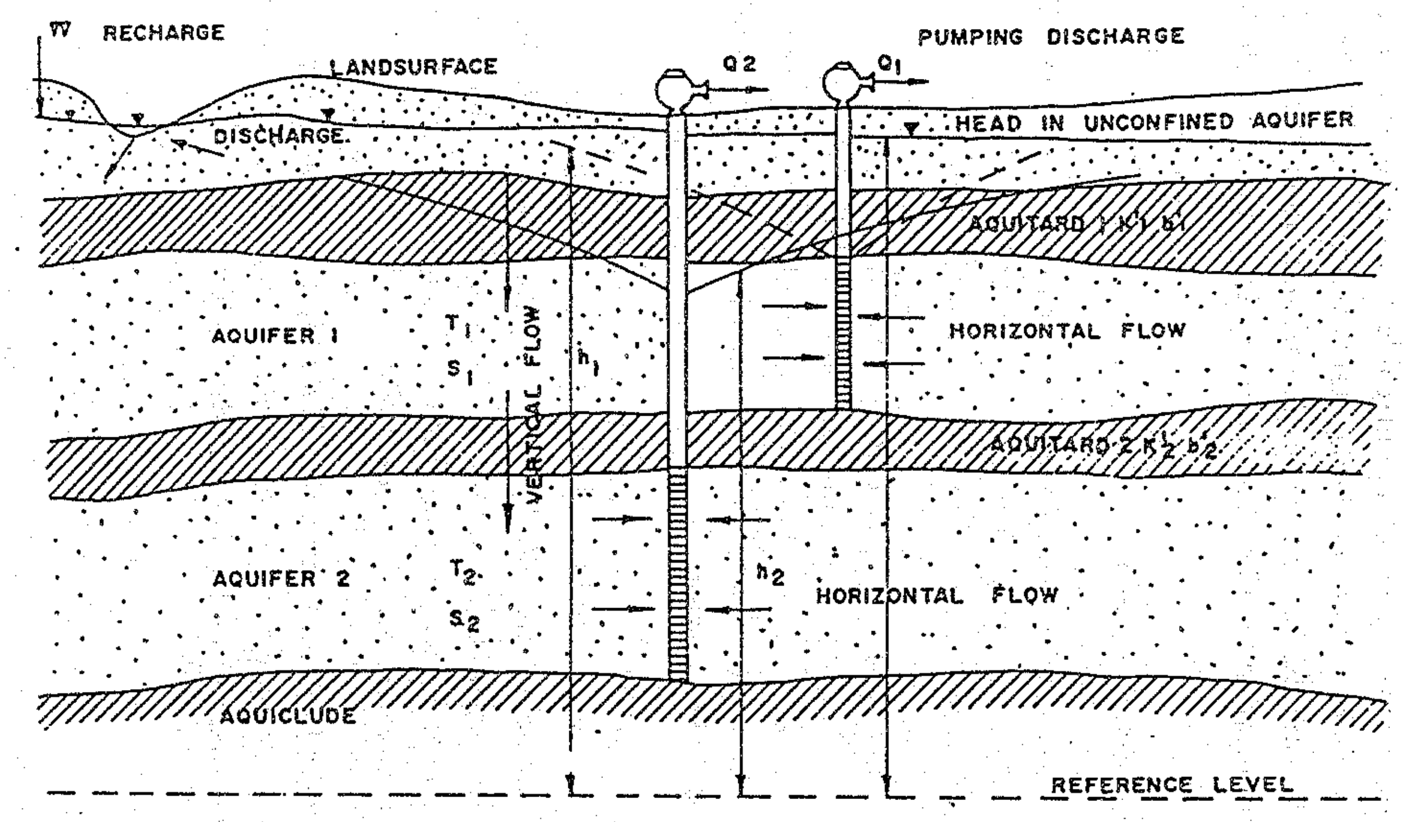


Fig. 7-6 Generalized Cross Section of Quasi-Three Dimensional Aquifer Simulation Model

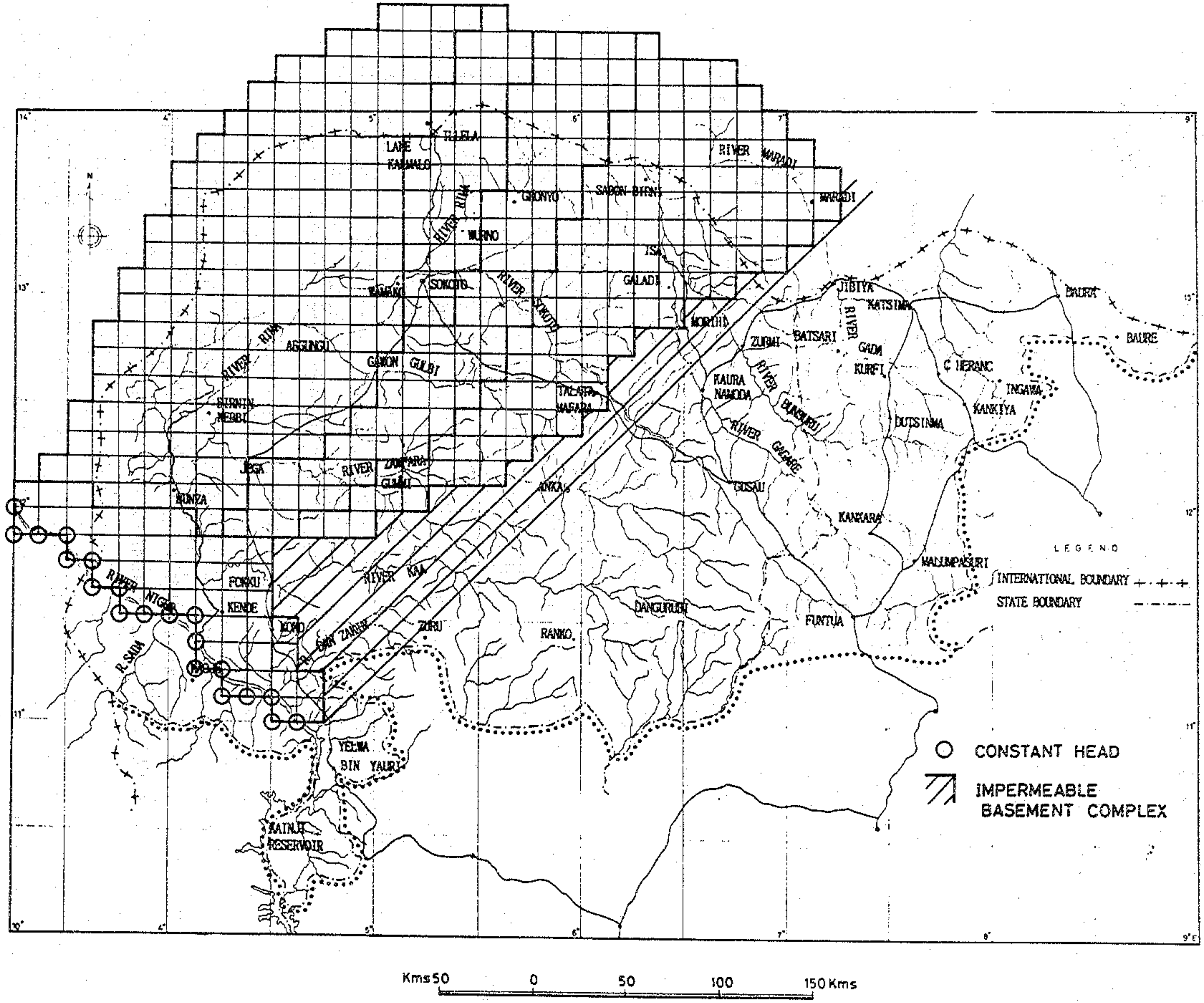


Fig.7-7 Finite Element and Boundary Conditions Used in the Model

(3) Aquifer parameters

Aquifer parameters were determined based on the results of water level observations and pumping tests carried out in the study area. When sufficient records were not available to determine a parameter, the general standard value was applied.

The parameters were given to each grid in each aquifer.

a. Thickness of aquifers (b)
   Based on hydrogeological cross sections given in Fig. 4-6, an aquifer thickness map for each aquifer was prepared for the three aquifers ; Gwandu, Rima and Gundumi aquifers (Fig. 7-8).
   Thickness of the Kalambaina aquifer was assumed to be 30 m constantly over the area.

b. Permeability (K)
   Permeability of the aquifers was estimated based on the borehole records constructed by the SARDA.
   Permeability for the aquifers ranges :

Tab. 7-6 Estimated Permeability (m/day)

Aquifer	Minimum	Maximum	Average
Gwandu formation	0.07	274	24.0
Kalambaina formation	0.09	1288	79.9
Rima group	0.02	198	16.0
Gundmi-Illo formation	0.08	439	23.1
Basement complex	0.01	195	2.6

c. Transmissibility (T)
   Transmissibility was calculated by multiplying the permeability by the thickness of an aquifer. Transmissibility obtained by pumping tests (Tab. 4-10) was also used.

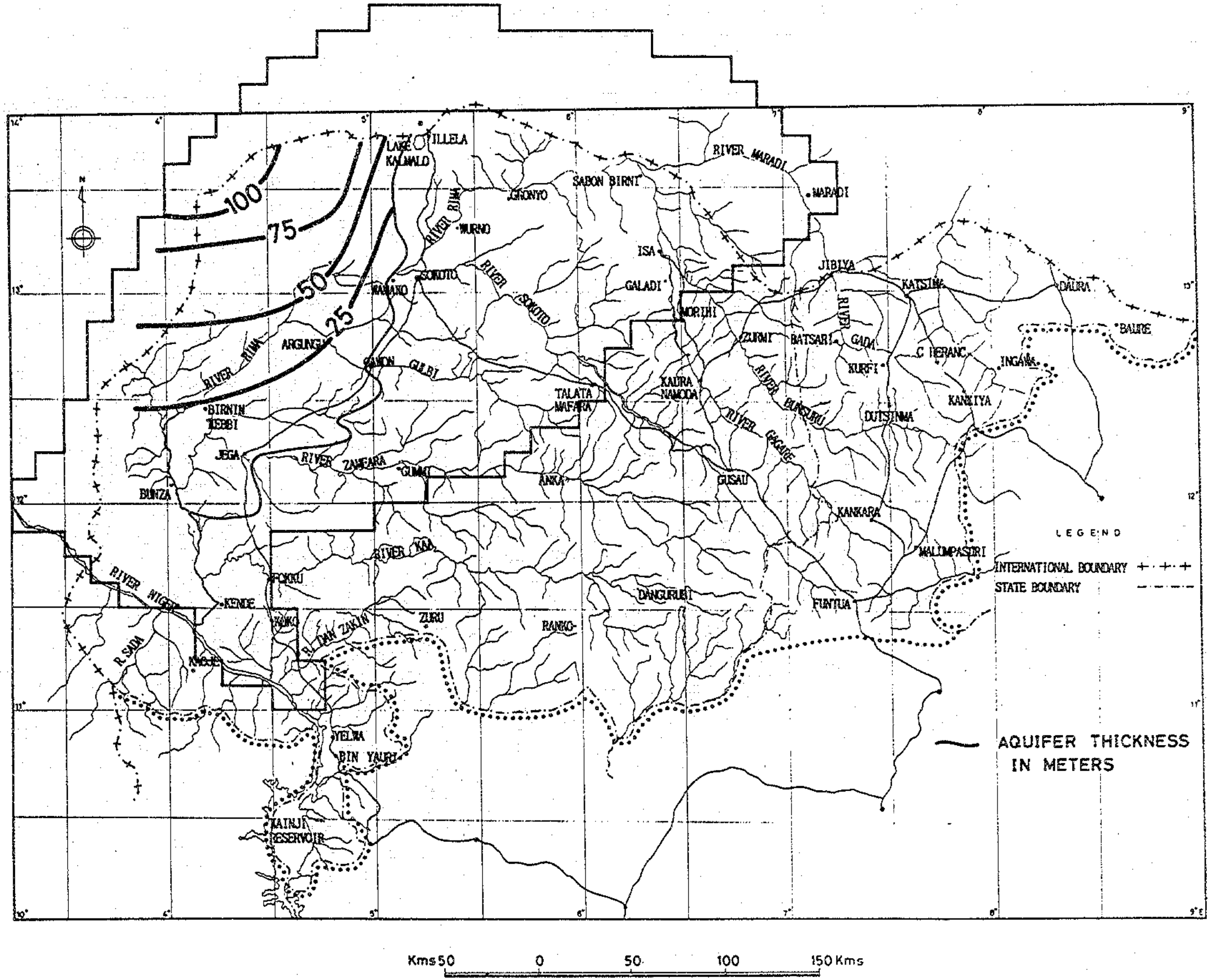


Fig. 7-8(1) Aquifer thickness of the Gwandu Confined Aquifer

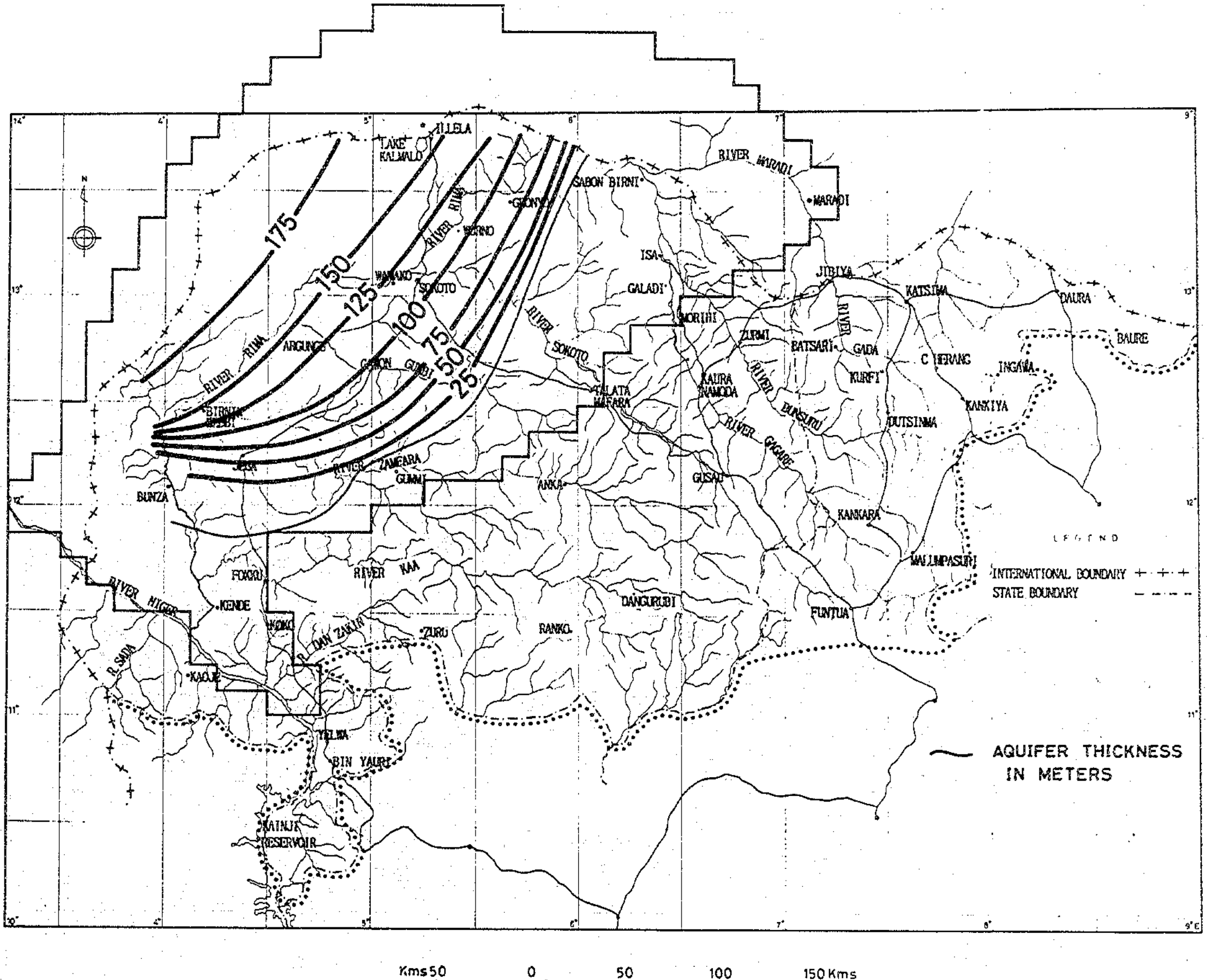


Fig. 7-8(2) Aquifer thickness of the Rima Confined Aquifer

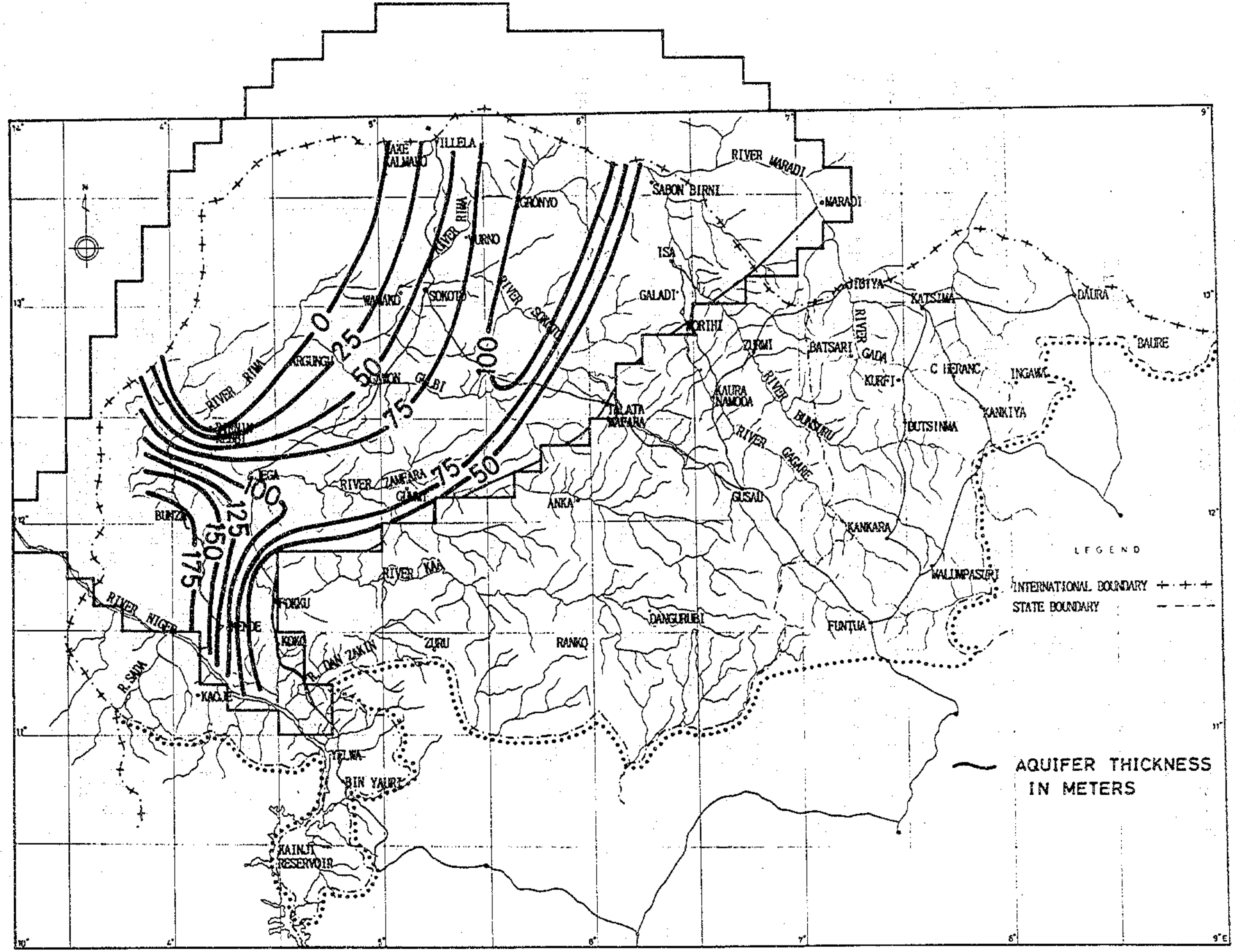


Fig. 7-8(3) Aquifer thickness of the Gundumi Confined Aquifer

d. Storativity (S)

Few records on storativity are available in the study area.

Therefore, storativity for a confined aquifer was determined by the theoretical equation,

$$S = Ss * b \quad \text{.............................} \quad (7\text{-}12)$$

where, Ss : Specific storage

Typical specific storage ranges for selected materials are given in Tab. 7-7. Specific storage of 1.5×10^{-5} was selected for Eq. (7-12). The value is equivalent to the typical value for dense sand.

Since the Kalambaina aquifer is unconfined, specific yield of 0.025 was applied for the aquifer as storativity. The specific yield corresponds to the typical value for limestone (Tab. 7-3).

e. Leakage (k'/b')

Leakage is the aquitard parameter which defines vertical leakage. The value is obtained by dividing permeability by the thickness of an aquitard. Thickness of the aquitards ranges 30m to 60m, according to the results of existing geological borings.

Aquitard permeability was assumed to be 5×10^{-8}cm/sec throughout the model.

Table 7-7 Representative Specific Storage Ranges (Domenico, 1965)

l/m

Material	Specific Storage
Soft Clays	$1.9 \times 10^{-3} \sim 2.4 \times 10^{-4}$
Stiff Clays	$2.4 \times 10^{-4} \sim 1.2 \times 10^{-4}$
Very stiff Clays	$1.2 \times 10^{-4} \sim 8.5 \times 10^{-5}$
Loose Sands	$9.4 \times 10^{-5} \sim 4.6 \times 10^{-5}$
Dense Sands	$1.9 \times 10^{-5} \sim 1.3 \times 10^{-5}$
Dense Gravels	$9.4 \times 10^{-6} \sim 4.6 \times 10^{-6}$
Rocks with Cracks	$1.9 \times 10^{-6} \sim 3.0 \times 10^{-7}$
Solid Rocks	$3.0 \times 10^{-7} \sim$