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FOUR-DIMENSIONAL RESPONSE OF THE AQUIFER AND AQUITARD SYSTEM IN TOKYO TO GROUNDWATER WITHDRAWAL AND REGULATION

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ABSTRACT

The aquifer-aquitard system in the lowland and upland in Tokyo Metropolitan area had been under great stress due to groundwater withdrawal after the second World War. The stress had resulted in one of the most severe land subsidence in the world. Groundwater management policy adopted by Tokyo Metropolice succeeded in stopping the land subsidence in the lowland by prohibiting the withdrawal, but groundwater is still in use in the upland area. Changes of the regional groundwater flow pattern in three-dimensional space were made clear by constructing the distribution map of the hydraulic head on two-dimensional vertical cross-section for years 1970, 1980, and 1987. Data used are the water level of observation wells, well logs with a single screen, and the static water level of wells for municipal water supply. From the revealed pattern of regional groundwater flow, roles of Tama and Sayama hills and the Tama River as groundwater recharge source, the function of Tachikawa fault in peventing groundwater flow, and areal differences in response of the aquifer-aquitard system to regulation and prohibition against groundwater withdrawal are made clear.

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INTRODUCTION

Groundwater issues in Japan have been changing from water resources development to environmental problems during the past twenty years. This is also true for Tokyo. Citizen in Tokyo are concerned about deterioration of ecosystem in urban environments. Water supplied through the hydrologic cycle, of which groundwater constitutes an important part, is thought to be the life blood of the terrestrial biosphere. Movement to conserve spring zone under a cliff of river terrace as an ecosystem is one of such examples. In this case, water is important not only as water resources but also as the life blood of urban ecosystem for citizen's mental amenity.

Groundwater development in Tokyo caused one of the most severe land subsidence in the world. The maximum accumulated amount of subsidence in the Koto lowland was 4.6 m (Kayane, 1991). This is a result caused by changes in groundwater flow due to groundwater withdrawal, but the actual changes in groundwater flow pattern in the subsurface environment were not made clear so far.

Tokyo Metropolice made a comprehensive and intensive groundwater survey in FY 1989–1991 (Environmental Conservation Bureau, Tokyo Metropolice, 1992) to investigate the past history and present situation of groundwater in Tokyo through analyses of topography, hydrogeology, paleohydrology, water balance, groundwater flow pattern, mechanism of spring discharge etc. The present report is an output from this project made by the authors participated in it.

CHAPTER I

STUDY AREA

1.1 Climate

Topographically, Tokyo Metropolice (Fig.1) can be divided into four categories; mountain, hill, upland, and lowland. The area investigated covers the upland and lowland.

There are six climatological stations in the upland and lowland which cover precipitation record for thirty years from 1958 to 1987. The annual mean precipitation of these stations ranges from 1331 mm at Sunamachi in the lowland to 1444 mm at Fuchu in the upland. The yearly precipitation at Otemachi near the civic center of Tokyo changes from 882 to 1804 mm/y with a difference of about 900 mm/y between the maximum and the minimum.

The mean annual potential evapotranspiration estimated by the Thornthwaite method for the same period at the same climatological stations ranges from 589 mm at Tokorozawa in the upland to 632 mm at Otemachi. Therefore the potential value for groundwater recharge is about 800 mm/y, that is 2.2 mm/d.

1.2 Hydrogeology

The upland whose surface is covered by thick tephra deposits is composed of uplifted fans called as the Musashino Upland formed by the Paleo-Tama River during the last glacial period after 130 ka B.P. The fan gravel layers are underlain by series of alternations of gravel, sand, and silt layers deposited on the lowland or in the shallow sea during Pleistocene. These layers are numbered from 42 to 96 in Figs.2 and 3 whose cross-sections are shown in Fig.1. The shaded layer on the cross-sections corresponds to the silt or silty layer. The layer numbered 10 is the alluvial deposit. Only two cross-sections are shown here, but more detailed description of hydrogeology including all east-west and north-south cross-sections in Fig.1 is given in the unpublished final project report by Environmental Conservation Bureau, Tokyo Metropolice.

1.3 Surface condition

Figure 1 shows the topographical map of the study area in which the black area indicates the urbanized area. The urbanized land surface especially that covered by impervious materials such as concrete or asphalt prevents rainwater infiltration, so that groundwater recharge is decreased. Areal change of the surface coverage by impervious materials was investigated by using air photographs taken at different periods and GIS data. In 1948 the wastern part of Ward ("Ku" in Japanese) District still included wide open space, but urbanization have been spreading westward. At present the whole upland area may be classified as urban or suburban area. Details of urbanization are not stated here, but necessary information including the applied analysis method can be obtained from the final project report mentioned above.

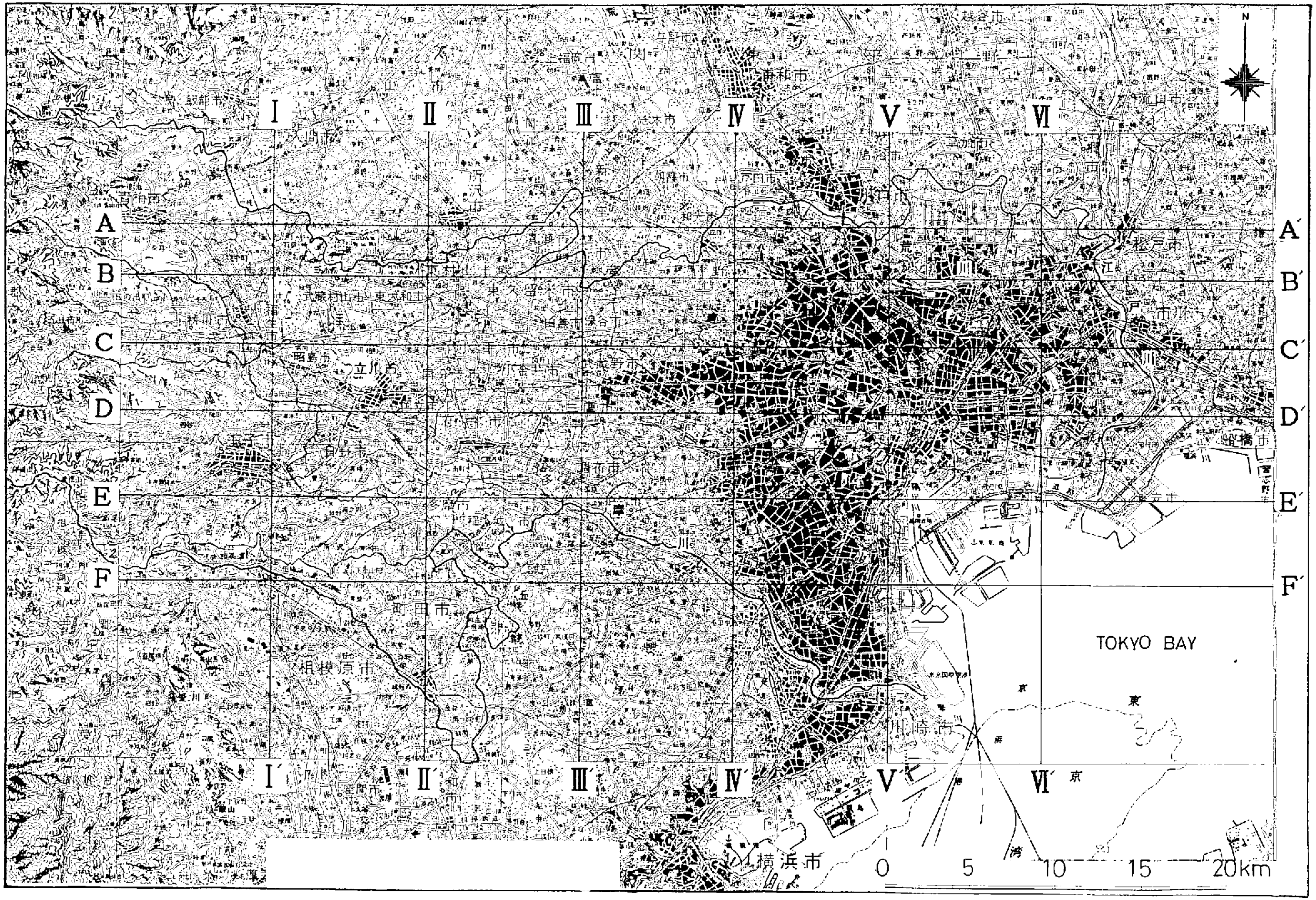

Fig.1 Location map of the study area

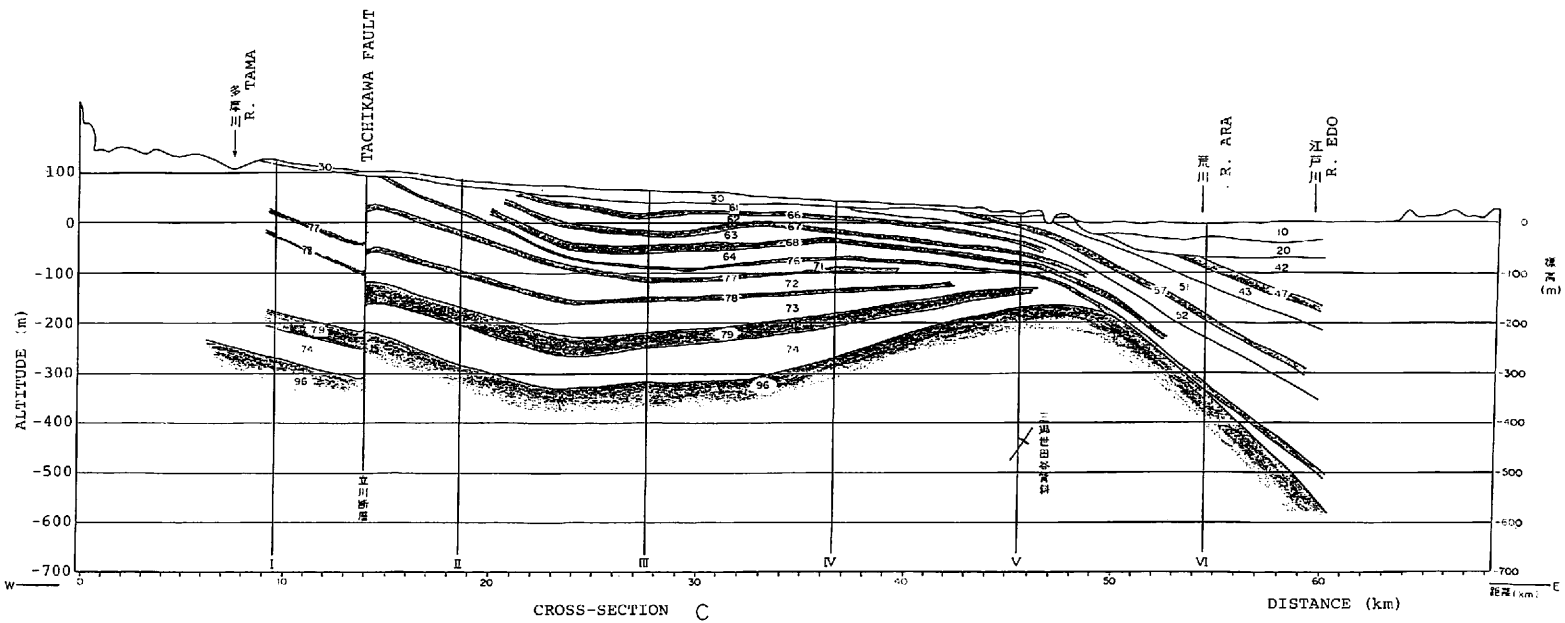

Fig.2 Hydrogeology of cross-section C–C′

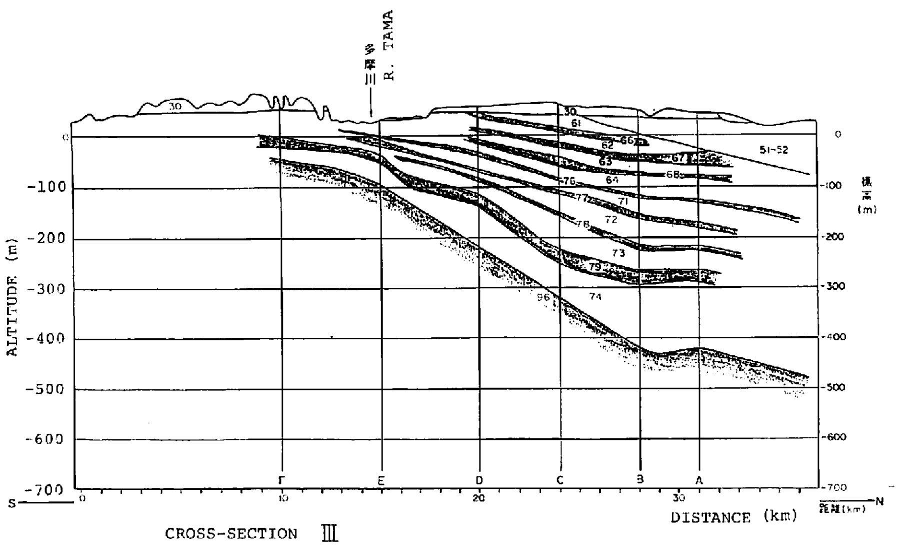

Fig.3 Hydrogeology of cross-section III–III′

CHAPTER II

GROUNDWATER USE

2.1 Changes of long-term groungwater level

Figure 4 shows typical examples of the groundwater level change in Tokyo. The top figure is the record of one of observation wells for monitoring land subsidence. There are about 80 observation wells in Tokyo Metropolice and plural wells with different depths were dug at a station. Minamisunamachi is located in the Koto lowland and No.1 indicates that this is the number one well among plural wells at the station. The water level is measured on T.P., which stands for Tokyo Pile.

The middle figure is the water level record of deep well at the Institute of Seismology, University of Tokyo located on the upland in Bunkyo-ku. The water level is measured on A.P., which stands for Arakawa Pile. The elevation of the top of the well casing is about 16 m above sea level. Observation began in October 1932. This record is presumably the longest record of groundwater level ever observed in Japan (Yamaguchi, 1986).

The history of groundwater development in Japan is shown in this figure. Groundwater withdrawals were mostly from Quaternary formations. With economic activity stagnant during the second World War, the water level recovered because of the diminution of groundwater withdrawal. The water level started to decline again in 1948 when post-war reconstruction began. During the period of so-called high economic growth in the 1960s, the decline of the water level reached a maximum, with a drop of 2.83 m in 1960. The decline showed in 1965 to a rate of 1.5 m per year, then recoded a level of 36.0 m below sea level at the end of 1971. The total decline from October 1932 to the end of 1971 was 38.97 m. The recovery of the water level after 1972 is the combined effect of two laws which regulate and/or prohibit groundwater utilization as will be stated in the next section.

The bottom figure is the record of static water level of a water well located at Shibasaki, Tachikawa City in the suburban Tokyo. The water level is recorded on T.P. The well have been in use but the water level was measured some time after stopping withdrawal. The occurrence time of the lowest water level is later than those in the top figure. This is due to later development of groundwater in the upland than in the lowland.

Figure 5 shows the water level of observation wells at different location. Numerals 1 to 4 in the figures indicate the well number from No.1 to No.4 respectively at the same station but with different depths. The water levels which are indicated by numerals at the screen position are those observed at the time of digging the wells. The times of digging are Nov. 1985 at Mizuho, Jan. 1982 at Musashimurayama, Jan. 1979 at Higashiyamato, Jan. 1980 at Tachikawa, Jan. 1984 at Higashimurayama, Jan. 1983 at Fuchu, Jan. 1981 at Koganei, Jan. 1976 at Higashikurume, and Jan. 1976 at Chofu respectively. Differences in the water levels with depth at the same station suggest existence of three-dimensional groundwater flow.

2.2 Groundwater withdrawal and regulation

Historical changes of the amount of groundwater withdrawal, hereafter expressed simply as abstraction, by Ward, City and Town are shown in Tables 1 and 2. The location of Ward, City, and Town in Tables 1 and 2 are indicated in Fig.6. Ward District is in the central part of Tokyo and the wastern part of Ward District is in the lowland. Drastic decrease in the abstraction after 1970 is a result of groundwater regulation adopted by Tokyo Metropolice. Two laws which regulate and/or prohibit groundwater

Table 1 Yearly change of mean amount of groundwater withdrawal for Central Tokyo (Ward District)
Unit: m^3/day

	Ward (ku)	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
1	Chiyoda	51,025	53,107	58,761	64,666	71,710	74,680	71,491	15,462	15,194	11,070	9,772	21,806	8,891	8,033	6,353
2	Chuo	22,062	22,830	25,773	27,733	30,716	33,556	30,375	13,034	13,515	6,614	6,641	3,710	3,466	3,216	2,511
3	Minato	21,671	22,247	26,101	25,853	27,931	27,977	26,465	6,119	7,669	7,034	6,906	5,606	4,344	4,232	3,850
4	Shinjuku	36,311	22,855	42,192	43,900	47,700	52,545	60,752	47,231	50,501	50,776	51,949	32,703	38,758	37,606	34,376
5	Bunkyo	10,986	11,022	12,762	13,337	14,518	15,948	15,992	16,091	17,388	17,574	18,402	18,271	14,452	18,743	16,977
6	Taito	28,245	28,691	33,031	34,727	38,083	38,860	42,306	20,689	9,053	5,145	5,025	9,237	5,739	6,012	5,761
7	Sumida	33,221	31,282	37,584	34,295	32,547	30,848	21,626	6,567	6,904	6,467	3,317	8,506	4,524	4,486	4,005
8	Koto	25,331	29,483	36,143	31,977	31,243	30,240	23,500	7,187	3,804	1,886	1,843	2,338	2,841	2,070	1,685
9	Shinagawa	21,084	20,568	11,491	12,341	13,101	14,875	17,401	12,558	10,023	9,529	9,163	11,169	9,369	8,444	8,165
10	Meguro	6,193	6,222	7,198	7,572	8,261	8,803	9,483	9,740	9,752	9,654	10,093	3,062	2,597	2,696	2,676
11	Ota	21,757	19,846	22,438	19,141	17,952	25,116	26,690	22,142	21,555	17,503	18,182	19,956	15,808	15,878	15,045
12	Setagaya	18,925	18,947	21,472	23,257	25,391	28,972	30,326	29,828	27,223	28,445	29,271	14,821	11,441	12,354	11,069
13	Shibuya	9,190	9,134	10,673	11,055	11,999	14,323	13,479	12,872	13,148	13,586	15,982	11,543	8,481	8,457	8,599
14	Nakano	6,007	6,016	6,910	6,901	8,653	11,733	9,008	9,474	7,433	4,172	3,963	9,559	8,824	9,511	9,513
15	Suginami	36,496	36,193	38,156	37,675	38,202	38,527	36,754	33,471	32,930	32,333	30,516	50,227	42,648	38,052	32,877
16	Toshima	10,268	10,466	12,414	14,760	16,022	18,982	14,519	13,771	14,190	14,168	13,898	18,446	19,042	19,470	18,723
17	Kita	118,053	123,527	133,761	139,843	148,129	141,303	120,927	112,508	96,120	81,885	84,428	86,061	62,019	22,876	19,264
18	Arakawa	22,617	24,073	23,168	23,582	23,919	22,335	11,946	9,300	8,890	9,031	8,915	10,757	7,244	6,833	4,218
19	Itabashi	55,616	52,076	73,009	65,387	83,392	82,988	96,364	83,002	82,357	86,209	83,714	108,084	91,298	49,698	46,754
20	Nerima	20,589	20,284	24,066	26,241	29,015	27,458	28,519	31,093	40,167	32,125	29,796	40,300	36,374	37,440	33,359
21	Adachi	73,493	80,034	82,037	82,136	88,077	90,811	77,088	74,152	55,070	52,845	68,479	74,889	53,356	22,645	21,047
22	Katsushika	57,876	51,799	59,722	60,710	68,045	67,625	67,036	62,971	52,843	52,342	50,937	59,165	48,479	26,046	22,152
23	Edogawa	65,797	73,767	71,515	72,279	72,768	68,762	35,276	36,062	36,792	34,870	33,093	36,741	34,116	37,550	32,191
	(Sub-total)	772,813	777,469	870,377	879,368	947,304	967,267	887,325	685,324	632,521	585,263	594,285	656,957	534,111	402,348	361,170

	Ward (ku)	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
1	Chiyoda	4,668	3,744	3,310	3,081	2,967	3,528	3,908	3,668	3,682	3,577	3,306	3,312	3,222	3,256
2	Chuo	763	573	563	557	623	654	646	645	652	712	708	712	675	690
3	Minato	3,918	3,454	3,212	3,141	2,845	2,709	2,175	2,579	2,486	2,572	2,450	2,342	2,355	2,394
4	Shinjuku	21,219	15,687	13,987	11,469	8,744	7,474	6,765	7,515	7,244	7,084	6,803	7,037	6,890	6,792
5	Bunkyo	11,721	8,155	6,366	5,787	5,495	5,564	5,234	4,902	4,832	5,201	5,278	4,715	4,861	3,884
6	Taito	4,695	3,574	3,116	3,069	2,851	2,845	2,807	2,743	2,681	2,664	2,853	2,885	2,895	2,695
7	Sumida	3,692	3,790	3,803	3,659	3,715	3,625	3,457	3,341	3,264	3,270	3,321	3,311	3,263	3,234
8	Koto	1,612	1,421	1,135	1,129	1,126	1,126	1,126	1,057	1,057	1,057	1,057	1,057	1,057	1,057
9	Shinagawa	7,603	6,319	5,766	5,483	5,425	5,333	5,120	5,197	4,956	4,726	4,590	4,593	4,472	4,375
10	Meguro	2,157	2,024	1,920	1,880	1,588	1,544	1,623	1,643	1,602	1,581	1,611	1,668	1,624	1,621
11	Ota	12,280	10,223	9,237	7,854	7,428	7,192	6,615	6,505	6,219	5,813	5,331	5,365	5,447	5,300
12	Setagaya	9,806	8,285	7,664	7,304	6,810	6,618	6,697	6,692	6,753	6,627	6,380	5,816	5,699	5,631
13	Shibuya	7,095	5,499	4,402	3,666	3,629	3,359	3,032	2,866	2,734	2,739	2,732	2,744	2,694	2,769
14	Nakano	8,222	6,046	7,177	5,176	4,782	4,525	4,249	4,375	4,105	3,959	4,038	3,986	3,818	3,951
15	Suginami	27,423	26,389	24,520	24,206	23,653	22,520	23,508	23,941	24,661	11,645	11,496	11,513	11,410	12,957
16	Toshima	13,899	9,016	7,179	6,195	6,383	6,163	6,001	5,552	5,228	5,239	5,137	5,075	4,952	4,966
17	Kita	11,234	6,817	7,486	7,621	7,847	7,035	6,850	6,713	6,323	5,792	5,507	5,489	5,438	5,407
18	Arakawa	3,890	3,675	3,664	3,612	3,614	3,041	2,824	2,819	2,821	2,760	2,759	2,779	2,756	2,758
19	Itabashi	27,306	16,903	15,589	14,670	14,487	14,054	13,025	12,456	11,619	10,644	10,437	10,367	9,621	9,445
20	Nerima	27,771	22,658	20,240	19,607	19,249	17,757	18,667	16,637	16,951	16,730	17,190	16,482	16,167	16,829
21	Adachi	17,469	14,435	13,575	8,600	7,617	7,411	7,605	7,537	7,451	7,337	7,300	7,284	7,258	7,264
22	Katsushika	18,890	15,089	13,494	8,190	6,316	6,060	5,948	5,929	5,946	6,031	6,025	6,005	5,975	5,983
23	Edogawa	25,900	12,362	7,167	6,151	6,589	6,344	4,092	3,634	3,632	3,635	3,601	3,612	3,616	3,612
	(Sub-total)	273,233	206,138	184,572	162,107	153,783	146,481	141,974	138,946	136,899	121,395	119,910	118,149	116,165	116,870

Table 2 Yearly change of mean amount of groundwater withdrawal for Tama District (City and Town)
Unit: m^3/day

	City or Town	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
24	Hachioji	9,733	13,214	17,540	21,976	28,215	32,922	48,299	51,233	45,052	44,956	41,579	48,169	42,561	44,519	44,265
25	Tachikawa	9,900	11,399	13,760	17,179	20,599	24,018	26,089	30,508	36,185	41,155	44,465	53,242	65,616	51,513	58,850
26	Musashino	9,042	12,602	16,035	19,469	22,903	26,336	28,599	31,519	36,081	33,517	35,043	37,894	40,448	43,492	37,732
27	Mitaka	8,599	11,229	14,133	19,181	24,230	29,279	31,077	36,911	39,920	45,819	48,587	60,951	54,774	58,330	60,788
28	Ome	66	517	957	1,404	1,411	1,411	1,437	1,496	1,591	1,584	1,584	1,113	699	811	818
29	Fuchu	6,952	8,470	10,528	16,293	23,432	31,345	38,569	43,677	53,320	58,707	62,544	84,564	88,107	90,223	97,160
30	Akishima	5,623	10,078	13,473	16,120	18,767	21,901	25,934	26,568	27,296	29,654	32,890	44,219	44,280	49,155	50,146
31	Chofu	9,579	10,052	12,151	15,907	18,322	21,811	26,796	34,583	44,806	45,424	45,610	53,607	54,443	50,026	52,496
32	Machida	3,944	5,394	6,219	7,451	9,034	11,144	22,796	27,914	26,166	22,499	21,395	26,235	25,812	27,424	28,721
33	Koganei	2,860	3,142	3,978	6,001	9,099	12,517	14,982	17,984	18,275	19,504	21,729	25,516	26,002	29,365	30,245
34	Kodaira	7,348	13,959	17,619	20,178	24,464	26,094	32,273	38,452	44,631	46,469	48,538	49,852	48,855	45,797	43,769
35	Hino	23,289	28,228	34,407	36,519	49,880	52,327	57,821	62,425	65,677	59,851	64,039	82,692	79,507	70,273	71,138
36	Higashimurayama	3,027	5,147	6,023	6,300	8,096	9,893	15,169	13,357	12,541	12,048	10,762	11,016	9,999	12,039	13,931
37	Kokubunji	903	1,022	6,497	7,534	8,513	10,201	11,329	14,706	18,357	20,574	22,891	23,981	27,405	28,274	28,449
38	Kunitachi	1,348	1,348	1,929	2,852	4,334	5,817	7,308	9,152	11,964	12,531	13,804	24,401	16,568	21,481	22,772
39	Tanashi	3,555	5,801	6,469	7,607	8,745	9,882	12,285	15,107	16,567	17,868	18,777	21,431	24,794	25,282	24,768
40	Hoya	5,711	5,938	7,175	7,257	7,590	8,577	9,565	10,997	14,239	16,866	19,546	23,925	27,617	27,268	27,318
41	Fussa	2,218	2,717	3,348	4,551	5,183	8,098	8,178	9,662	10,661	11,743	12,520	16,780	20,003	20,170	20,520
42	Komae	1,742	1,801	1,859	1,859	1,859	17,740	14,799	17,585	14,707	12,748	10,841	13,209	11,324	12,938	10,594
43	Higashiyamato	352	866	1,642	2,073	3,267	4,294	5,608	6,068	7,256	9,263	12,771	14,513	15,475	19,228	15,253
44	Kiyose	2,024	2,156	2,992	4,192	5,393	6,594	8,646	9,895	10,884	12,960	13,866	15,132	14,759	16,017	14,553
45	Higashikurume	616	862	3,098	3,133	6,160	7,163	8,923	9,170	12,074	12,257	16,060	22,505	21,052	37,390	31,988
46	Musashimurayama	0	0	6,322	6,322	6,360	7,242	10,175	12,234	14,483	21,270	22,959	34,030	31,061	31,016	30,405
47	Tama	120	121	121	200	1,926	3,653	4,525	5,825	6,305	7,143	8,100	9,713	11,249	12,709	11,465
48	Inagi	0	26	133	1,060	1,060	1,060	1,848	2,384	3,070	5,996	7,960	12,561	14,563	20,045	23,694
49	Akikawa	0	0	0	0	14	77	1,592	2,541	2,827	3,248	4,185	6,248	6,869	6,824	7,706
50	Hamura	634	634	913	1,206	2,442	2,867	3,814	5,016	6,336	7,870	9,426	12,958	15,419	13,170	14,522
51	Mizuho	0	60	79	79	231	803	1,753	2,360	2,777	2,958	3,193	6,280	3,926	5,803	4,750
	(Sub-total)	119,185	156,783	209,400	253,903	321,529	395,066	480,189	549,329	604,048	636,482	675,664	836,737	843,187	870,582	878,816
	(Grand total)	891,998	934,252	1,079,777	1,133,271	1,268,833	1,362,333	1,367,514	1,234,653	1,236,569	1,221,745	1,269,949	1,493,694	1,377,298	1,272,930	1,239,986

	City or Town	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
24	Hachioji	42,418	36,767	36,365	34,382	34,658	34,516	30,649	28,490	29,703	27,097	26,423	25,529	24,565	25,795
25	Tachikawa	54,416	56,023	56,504	50,917	50,248	47,879	17,469	47,378	44,290	11,515	41,395	39,209	38,774	36,737
26	Musashino	37,393	37,392	35,467	34,463	36,429	35,094	34,331	35,039	35,372	35,322	34,183	34,544	34,897	35,182
27	Mitaka	59,608	57,134	54,450	54,737	53,552	49,889	47,530	45,109	45,003	43,446	41,617	41,518	40,773	40,170
28	Ome	1,169	1,880	1,950	2,101	2,262	2,318	2,143	2,189	2,602	2,543	3,221	4,997	3,297	3,545
29	Fuchu	86,131	86,338	84,449	77,188	77,690	79,138	76,189	70,921	63,179	70,221	67,716	62,205	58,713	62,399
30	Akishima	45,180	45,481	44,297	43,720	43,923	43,381	42,294	43,156	42,210	42,717	44,526	44,450	45,745	45,521
31	Chofu	52,051	58,901	61,810	55,114	63,747	62,431	61,981	57,090	61,844	57,909	55,199	54,834	53,935	56,803
32	Machida	26,502	23,293	21,997	21,955	21,235	20,287	20,217	19,712	17,413	15,836	14,281	14,599	14,327	12,239
33	Koganei	30,457	31,045	30,363	30,657	31,046	30,862	28,875	26,665	22,748	24,090	25,472	24,150	20,617	20,182
34	Kodaira	38,133	32,198	32,244	32,053	31,728	26,142	23,774	22,280	19,698	18,551	18,454	17,139	17,077	16,711
35	Hino	65,834	63,461	57,074	53,004	53,105	52,761	51,162	47,439	43,756	39,396	39,325	39,234	37,388	30,789
36	Higashimurayama	12,446	12,314	12,916	11,630	11,231	11,268	10,795	10,617	9,286	8,595	7,901	7,812	6,389	6,280
37	Kokubunji	28,014	28,525	25,809	26,856	27,509	28,558	28,155	25,939	23,927	24,705	23,583	23,354	21,278	21,961
38	Kunitachi	22,888	24,235	23,845	23,185	23,827	24,229	23,608	22,747	20,240	19,282	19,505	18,948	15,022	15,751
39	Tanashi	26,374	23,807	21,950	21,361	19,048	17,824	16,838	14,919	13,977	11,927	11,964	12,753	12,471	12,429
40	Hoya	25,417	22,073	21,037	21,504	19,668	17,864	16,066	15,679	14,206	14,247	13,912	13,272	12,237	12,140
41	Fussa	17,481	16,373	15,487	15,245	11,050	11,453	10,811	9,403	7,958	8,312	9,122	9,425	8,446	8,799
42	Komae	8,457	8,042	7,905	8,367	7,733	7,658	7,200	5,839	5,499	5,403	2,868	4,290	3,809	4,047
43	Higashiyamato	13,665	11,137	9,688	8,069	8,144	8,190	8,288	7,597	6,724	6,606	6,877	6,625	5,853	6,759
44	Kiyose	15,389	15,360	12,732	9,474	4,602	3,601	3,524	3,484	3,816	2,906	2,809	2,805	2,965	3,109
45	Higashikurume	31,516	29,001	28,186	25,861	20,271	23,201	20,755	22,351	19,178	17,148	16,731	17,216	16,459	9,582
46	Musashimurayama	27,196	24,565	20,681	18,242	18,391	16,844	14,694	13,198	11,686	10,416	10,445	10,023	10,197	10,586
47	Tama	10,031	9,804	9,006	8,908	8,497	9,239	8,949	7,758	7,418	6,459	7,150	7,439	6,185	6,830
48	Inagi	21,510	19,269	19,021	17,493	17,482	15,322	13,841	12,945	11,414	11,246	10,940	10,344	8,937	10,271
49	Akikawa	8,982	9,496	10,319	11,485	11,029	11,155	10,492	11,284	10,610	10,181	10,200	9,426	9,189	8,886
50	Hamura	22,708	20,432	27,693	27,835	28,706	29,011	30,163	31,333	31,969	34,022	32,017	31,087	30,697	28,725
51	Mizuho	4,180	3,728	3,272	2,932	2,931	2,818	2,605	2,304	2,171	1,722	1,797	1,687	1,605	1,281
	(Sub-total)	835,546	808,074	789,517	748,738	739,742	722,933	693,398	662,865	627,897	611,820	599,633	588,944	561,847	553,509
	(Grand total)	1,108,779	1,014,212	974,089	910,845	893,525	869,414	835,372	801,811	746,796	733,215	719,543	707,093	678,012	670,379

Sub-total is for Tama District only, grand-total is for whole Tokyo.

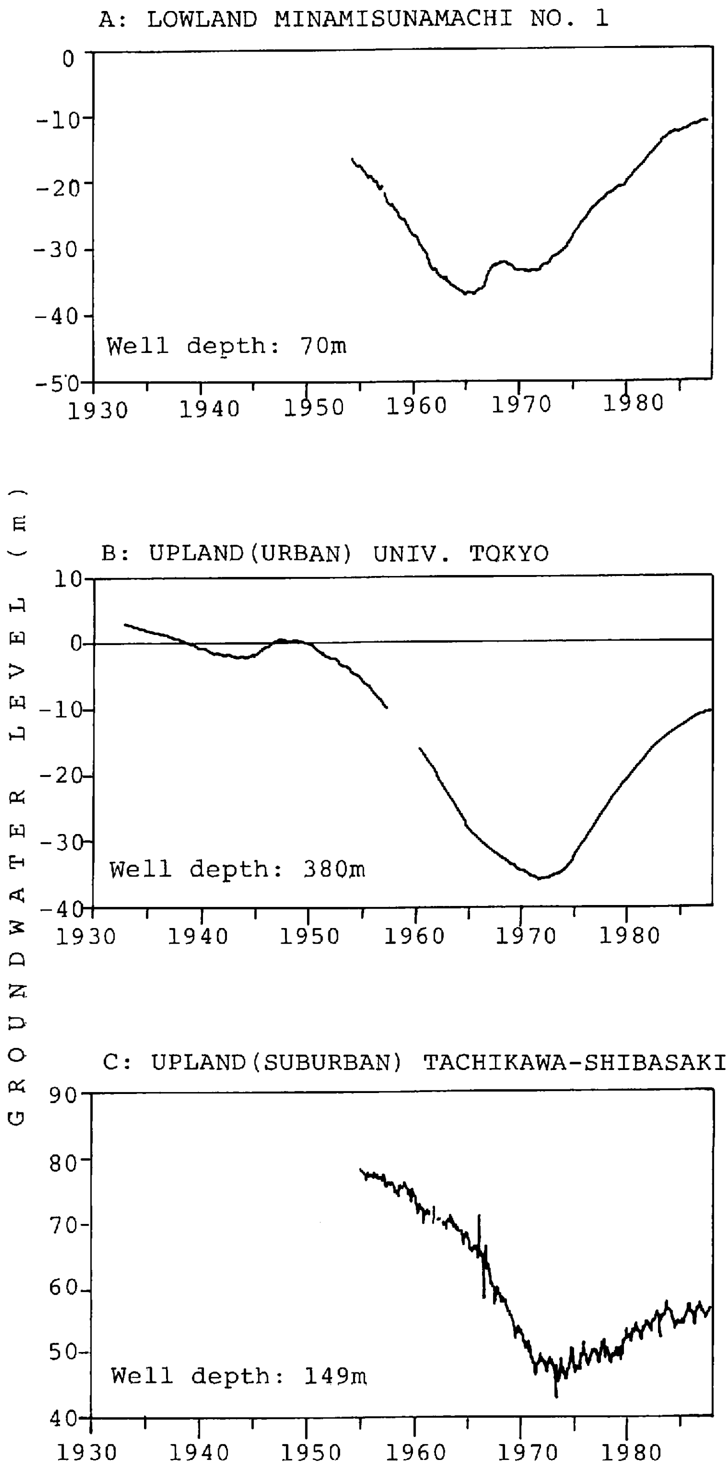

Fig.4 Changes of the long-term groundwater level in Tokyo

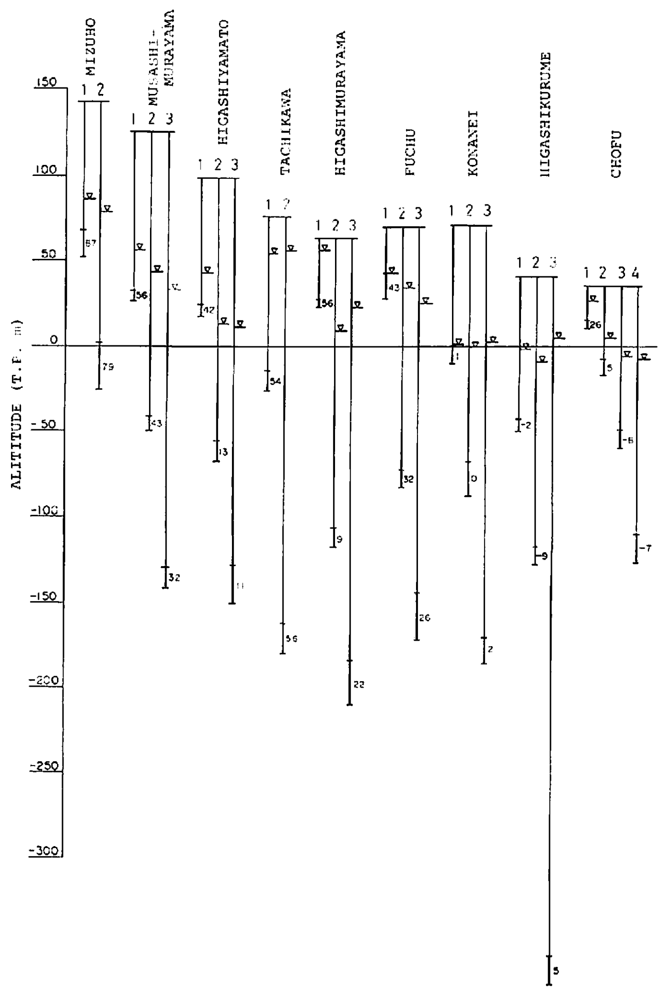

Fig.5 Differences in the water level in observation wells at the same station with different depths

utilization were established in Japan. One is the Industrial Water Law and the other is the Building Water Law. But Japan has no law regulating groundwater withdrawal for irrigation.

Regulations and restrictions in Ward District adopted under these two laws to prevent land subsidence are described in detail by Yamamoto (1984) or Kayane (1991). Tama District located in the upland has recorded no severe damage caused by land subsidence, so that regulation for groundwater withdrawal is not strict. Groundwater has been used mostly for drinking purpose. Figure 7 shows distribution of deep wells for municipal water supply in Tama District. Use of groundwater is prohibited even for the purpose of drinking in Ward District.

So called "optimal amount" of groundwater withdrawal has been sought experimentally in Tokyo. Figure 8 through Fig.11 are examples of the experiments. The amount of groundwater withdrawal is expressed in mm/day in these figures as abstraction. Figure 8 shows the history of abstraction and changes of the water level in observation wells. Sumida-ku is located in the Koto lowland and groundwater withdrawal was prohibited in early stage, so that the water level started recovering in 1965. The water table had been below the bottom of the observation well of Azuma-A in a part of 1960s and 1970s

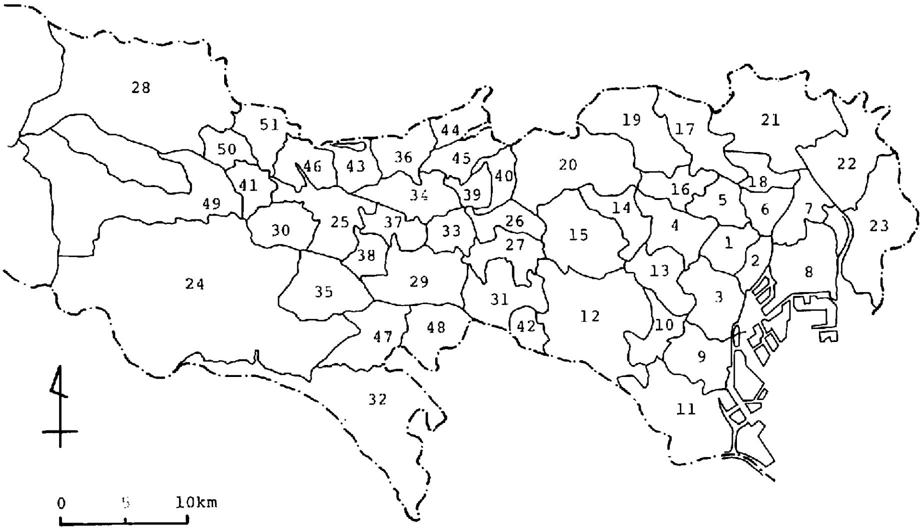

Fig.6 Numbers indicating municipal unit for Tables 1 and 2

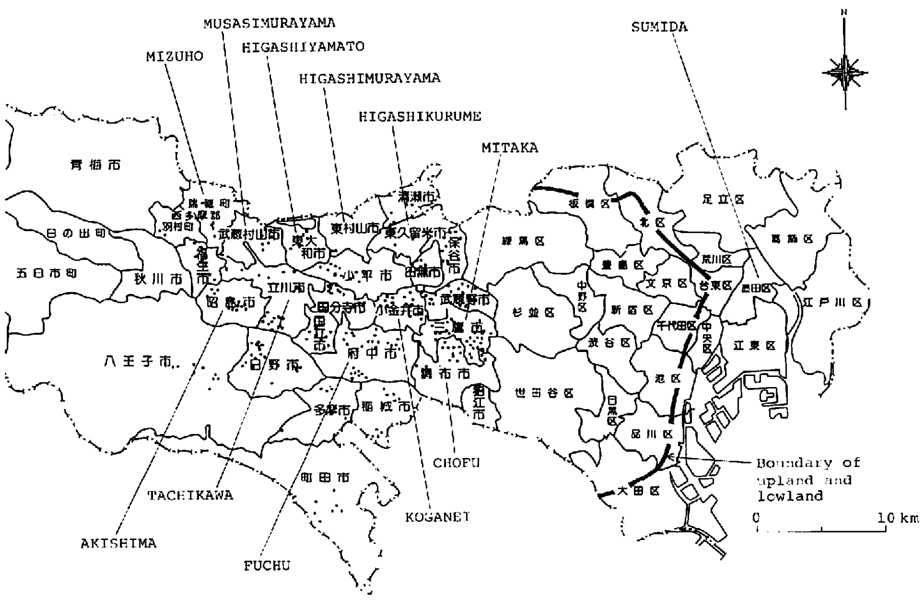

Fig.7 Distribution of wells for municipal water supply in Tama District

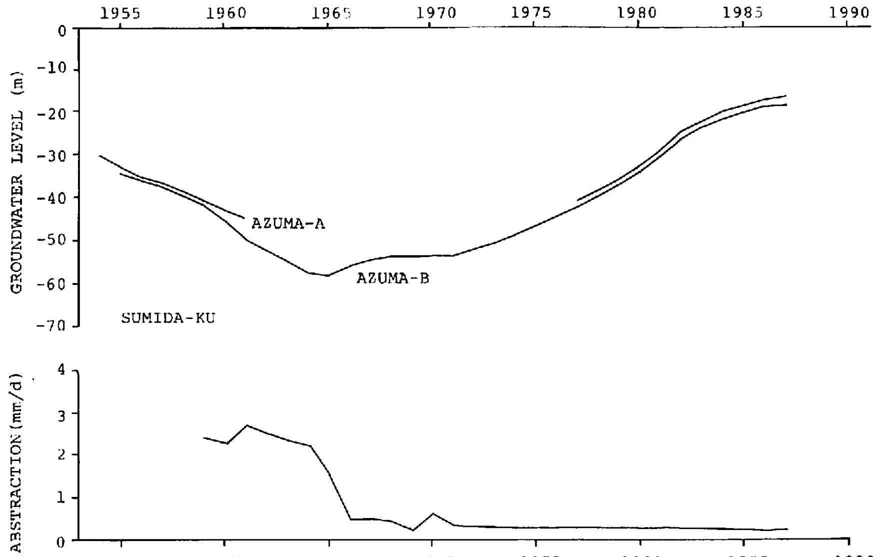

Fig.8 Relationship between the amount of groundwater withdrawal (abstraction) and the groundwater level for Sumida-ku

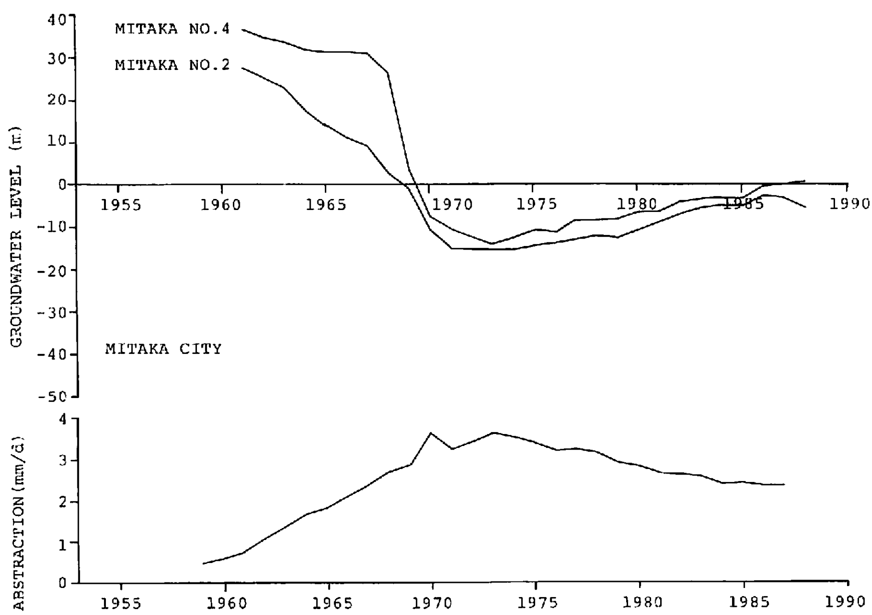

Fig.9 Same as Fig.8 but for Mitaka City

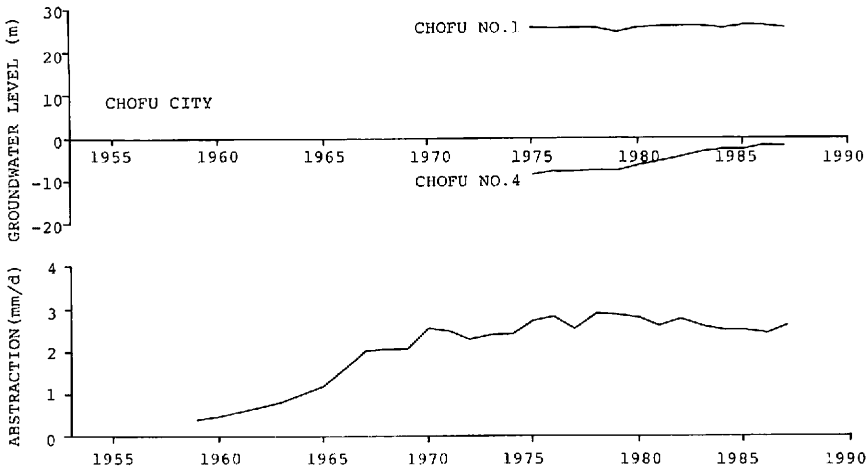

Fig.10 Same as Fig.8 but for Chofu City

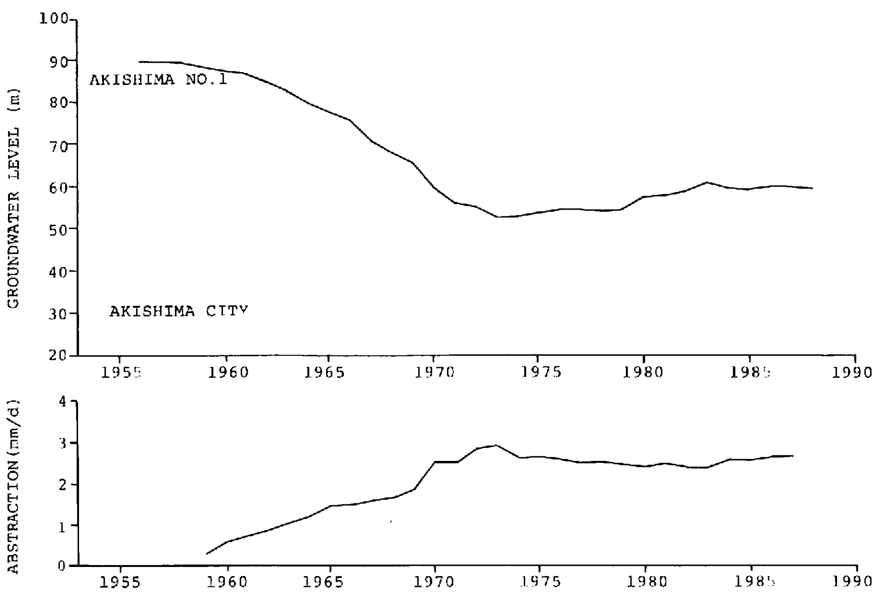

Fig.11 Same as Fig.8 but for Akishima City

so that no record was obtained during that period. In 1988 the water level was still in recovering stage.

Figure 9 is for Mitaka City located immediately west of Ward District. Sharp decline in the water level was not caused by the withdrawal in Mitaka City but by the withdrawal in Ward District. The water level started recovering responding to the regulation and restriction in Ward District.

Figure 10 is for Chofu City. A part of Chofu City is in the alluvial lowland of the Tama River, which is a source of groundwater recharge. The water levels in the city differ greatly with the depth of wells. In 1988 the water level in the deep well (No.4) was in quasi-steady condition with time.

Figure 11 for Akishima City located at the western margin of the Musashino Upland formed by the Paleo-Tama River. Records of the water level and the abstraction seem to indicate that the withdrawal in 1988 is in quasi-steady condition. By comparing these figures, Fig.9 throuth Fig.11, the "optimal amount" of withdrawal seems to be 2 to 3 mm/d in Tama District, that is in the upland area. The potential value of groundwater recharge in the upland is about 2.2 mm/d as explained before, so that the above range exceeds the potential value. Investigation into the groundwater balance revealed that an important source of groundwater recharge in Tokyo is the leakage from the waterworks pipeline. The result of water balance will be reported elsewhere.

CHAPTER III

CHANGES OF HYDRAULIC HEAD

3.1 Definition of the hydraulic head

Hubbert (1940) defined the potential which governs the movement of fluid in the porous media as follows, and named as the fluid potential, ϕ.

$$\phi = gz + \int_{p_0}^{p} \frac{dp}{\rho} + \frac{v^2}{2} \quad \cdots\cdots (1)$$

where g is the acceleration of gravity, z is the height above a datum level, ρ is the density of water, v is the velocity, p and p_0 are the water pressure at z and the datum level respectively. In the right hand side of Eq.(1), the first term indicates the gravity potential, the second term the pressure potential, and the third term the velocity potential. As the groundwater velocity is of the order of several meters per day or less, the velocity term is negligibly small compared with other two terms. If the water is assumed to be an incompressible fluid, Eq.(1) may be expressed with sufficient accuracy as

$$\phi = gz + \frac{p-p_0}{\rho} \quad \cdots\cdots (2)$$

Putting p_0 equals to the atmospheric pressure, and dividing Eq.(2) by g, we obtain the fluid potential as follows,

$$h = \frac{\phi}{g} = z + \frac{p}{\gamma} \quad \cdots\cdots (3)$$

where $\gamma = \rho g$ is the specific weight of water.

In Eq.(3) h is called the hydraulic head, z is the gravity head, and p/γ is the pressure head with the dimension [L]. The pressure head can be measured by the piezometer as the height of water column in it from the opened bottom. The gravity head is the height of the piezometer bottom above the datum level, so that the hydraulic head is measured as the water level in the piezometer above the datum level. The sea level is taken as the datum level in this study, so that the hydraulic head at the screen level in a well with a single screen is equal to the altitude of the water level in the well.

3.2 Basic data for determination of hydraulic head distribution

Basic data used for constructing the distribution of hydraulic head on the two-dimensional vertical cross-sections, A–A′ through F–F′ and I–I′ through VI–VI′ in Fig.1 are;

1) Water level record of the observation wells in Tokyo Metropolice
2) Well log record of the borehole with a single screen
3) Static water level record of the well for municipal water supply

These records are analysed in time and three-dimensional space, then plotted on respective cross-sections.

3.3 Determination of the water table

It is clear from the definition of the hydraulic head stated above that the level of water table indicates the hydraulic head at the level where the pressure head is zero, that means equal to the atmospheric pressure. Therefore the determination of the level of water table is of utmost importance in constructing the map of hydraulic distribution on the two-dimensional vertical cross-section.

Figure 12 is a partly enlarged figure of Fig.13 to show the importance of determination of the water table in constructing the distribution map of the hydraulic head. If we assume the level of the water table as indicated by the solid line (W.T.) in Fig.12, equi-head lines can be drawn as shown by the solid equi-head lines. Fortunately in this case one observation well record could be used to determine the water table, but if the data could not be available, and if we assumed that the water table was close to the land surface, then resultant equi-head lines would be those as shown by broken lines.

Generally speaking, however, as the observation wells are installed for the purpose of monitoring changes in deep aquifers, determination of the water table by using the observation well records only is quite difficult. In the following cross-sections, the level of water table was determined by trials and errors to find an uncontradictable picture of the hydraulic head distribution. But in case we could not determine the level of water table with confidence due to lack of reliable information, an alternate position of the water table is shown by the broken line. Observation of the level of water table is very important for management of groundwater. An appropriate network of observation system for measuring the water table fluctuation is necessary to investigate the groundwater balance, the three-dimensional flow pattern of groundwater, the interaction between groundwater and surface water and so on.

3.4 Distribution of the hydraulic head for 1970

Figure 13 through Fig.24 are the final result of the distribution of the hydraulic head on vertical two-dimensional cross-sections shown in Fig.1 for 1970, when groundwater levels recorded the lowest value or close to the lowest in the Koto lowland.

The most conspicuous feature is the contrast of vertical equi-potential lines in the Tama Hills in Fig.19 with horizontal ones in the Koto delta in Fig.13 though Fig.16. The former is the pattern where groundwater is not developed and still in natural condition, and the latter are the result of groundwater withdrawal which caused severe land subsidence.

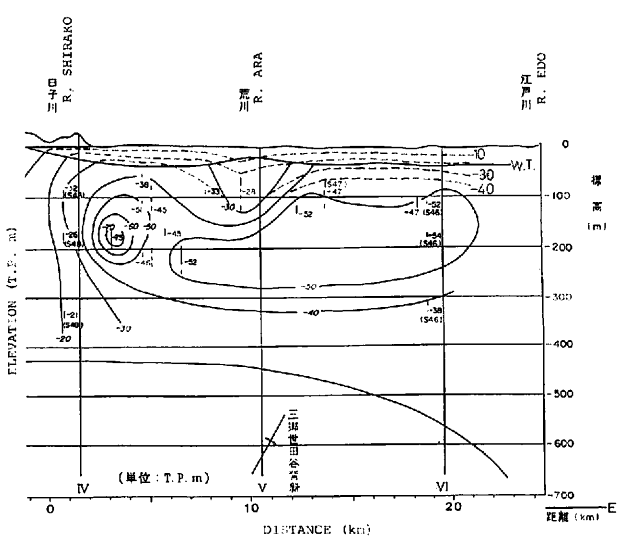

Fig. 12 Importance of the water table in drawing the equi-head lines

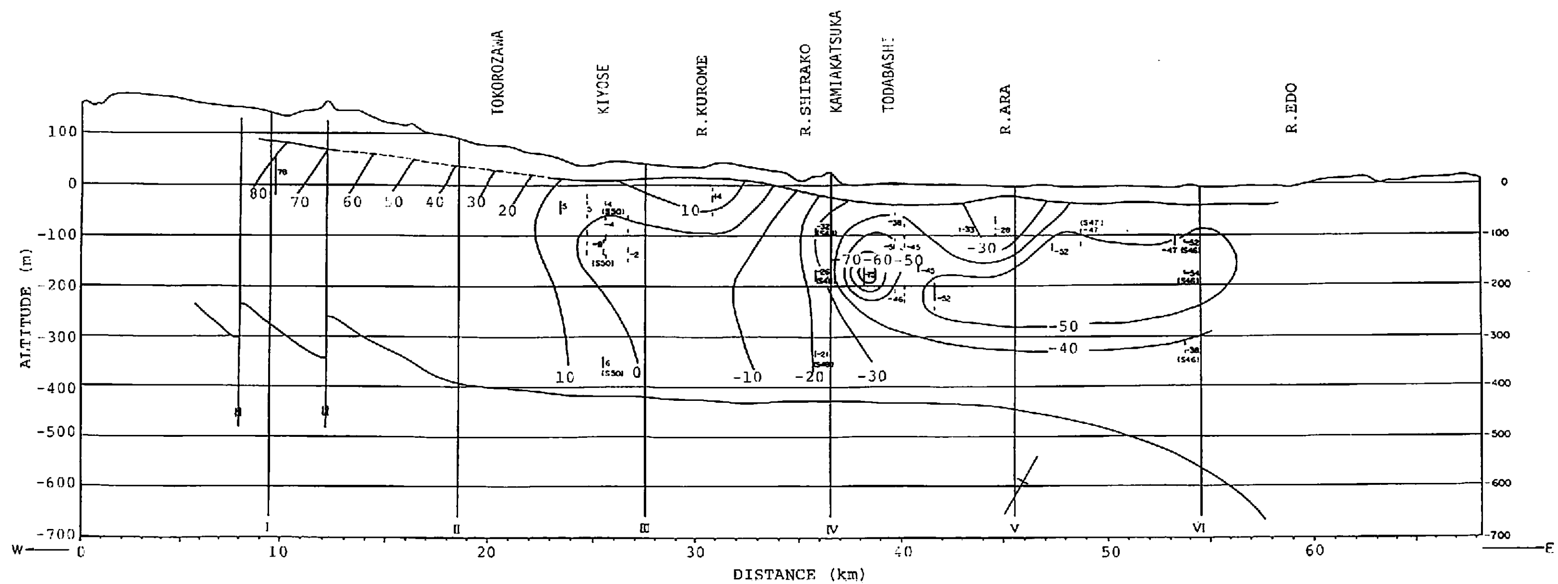

Fig.13 Distribution of the hydraulic head in 1970 on cross-section A–A′

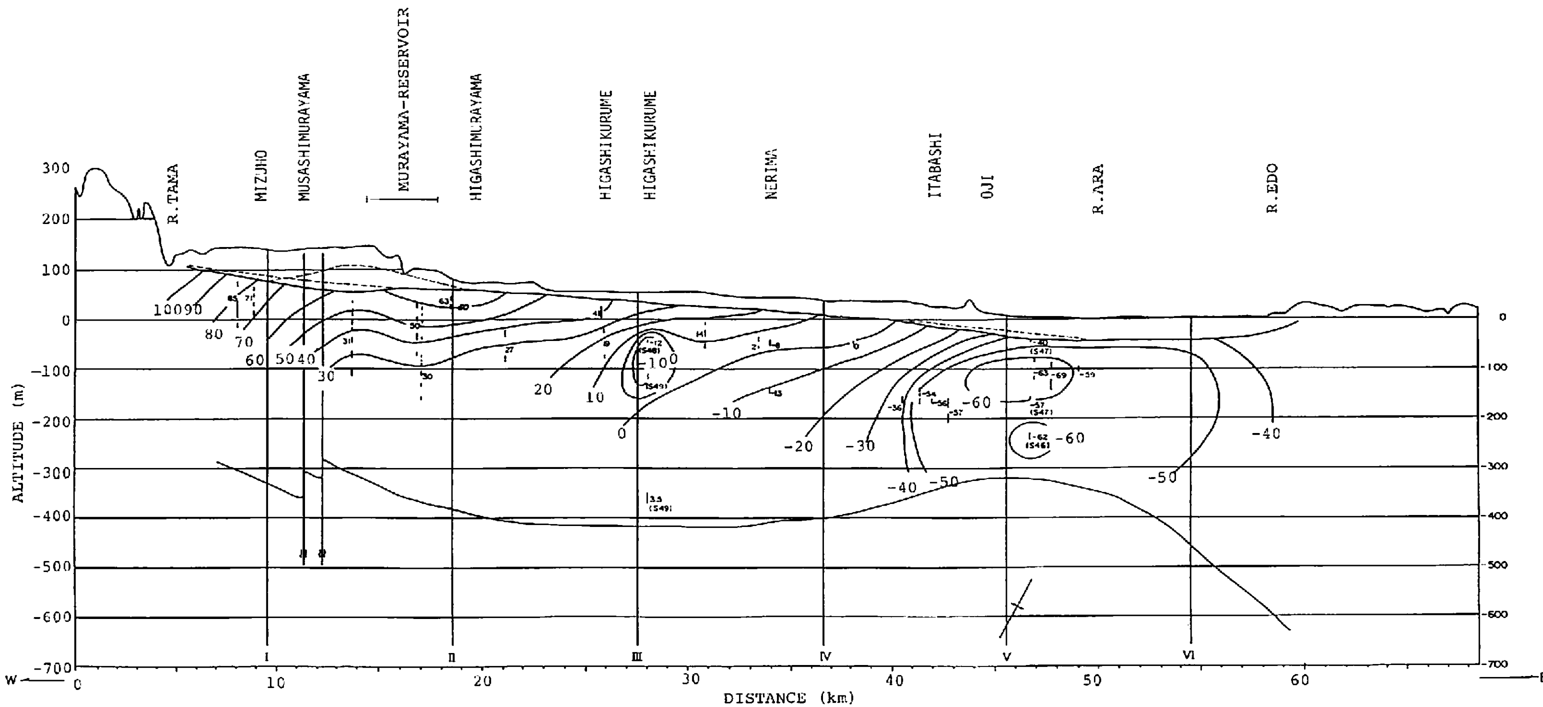

Fig.14 Same as Fig.13 but for B–B′

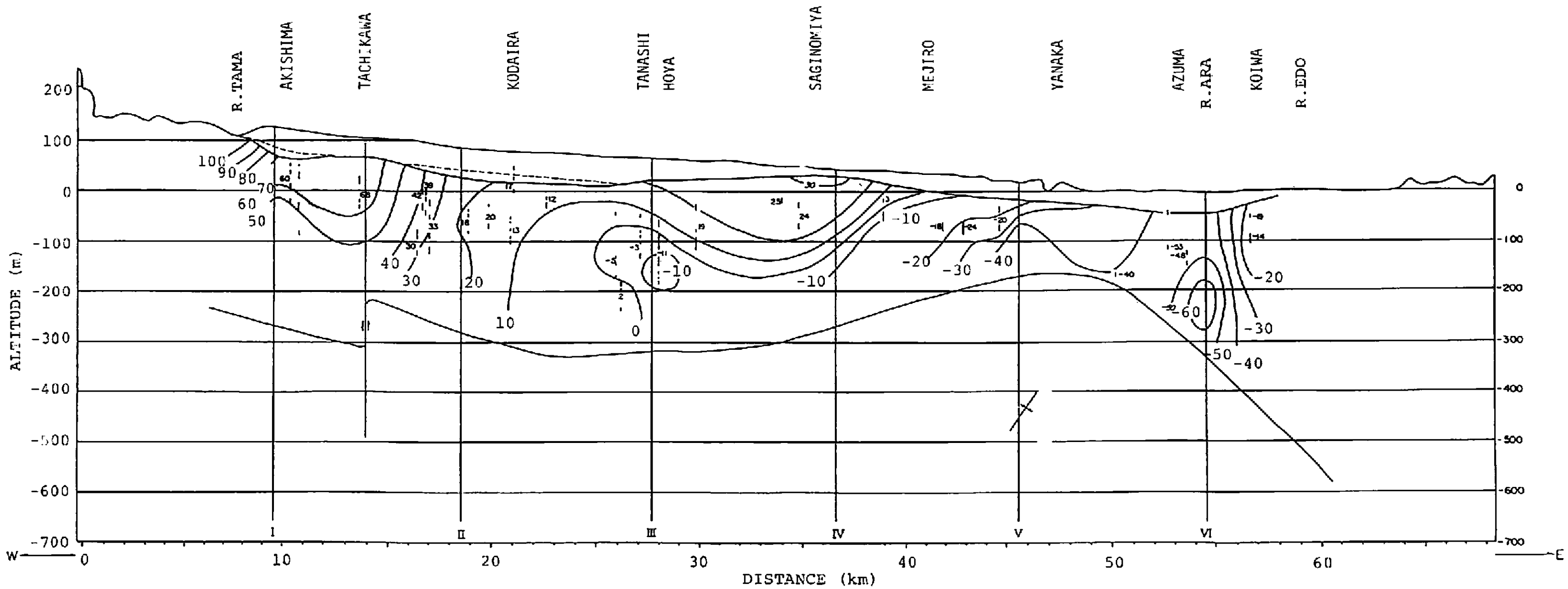

Fig.15 Same as Fig.13 but for C–C′

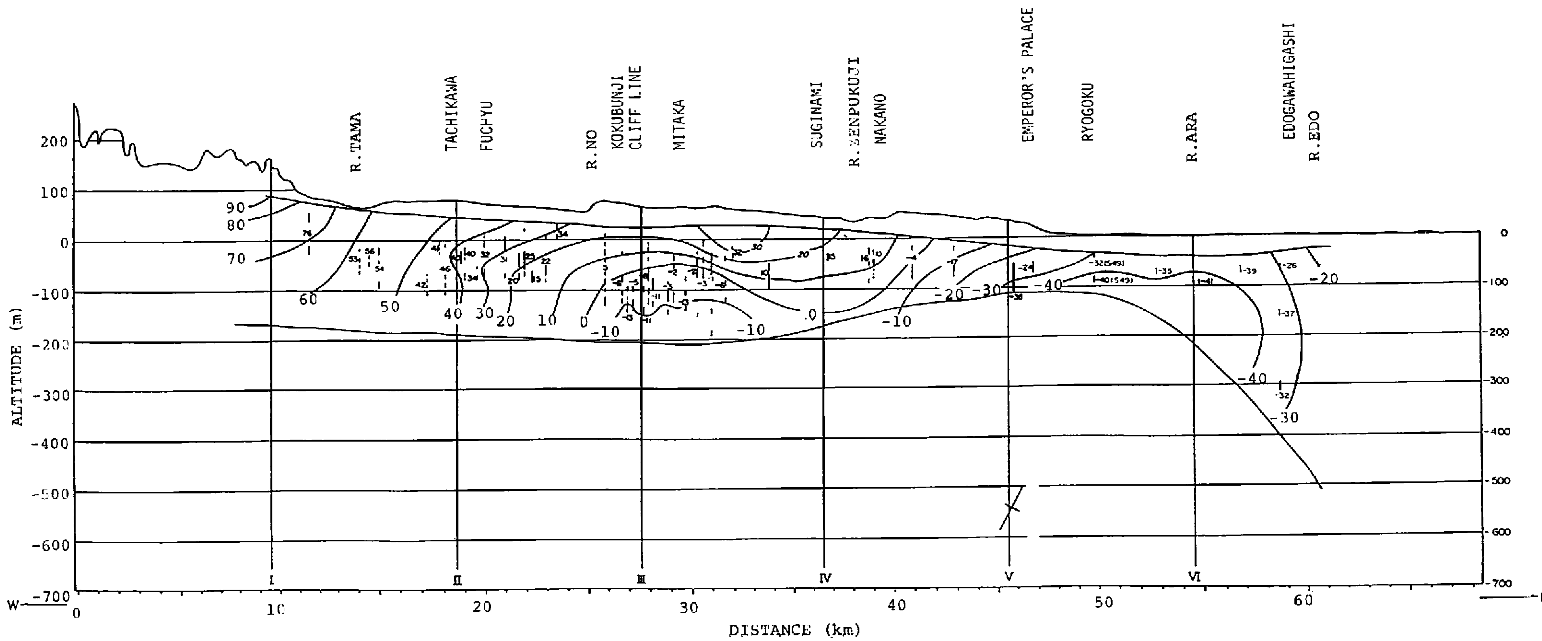

Fig.16 Same as Fig.13 but for D–D′

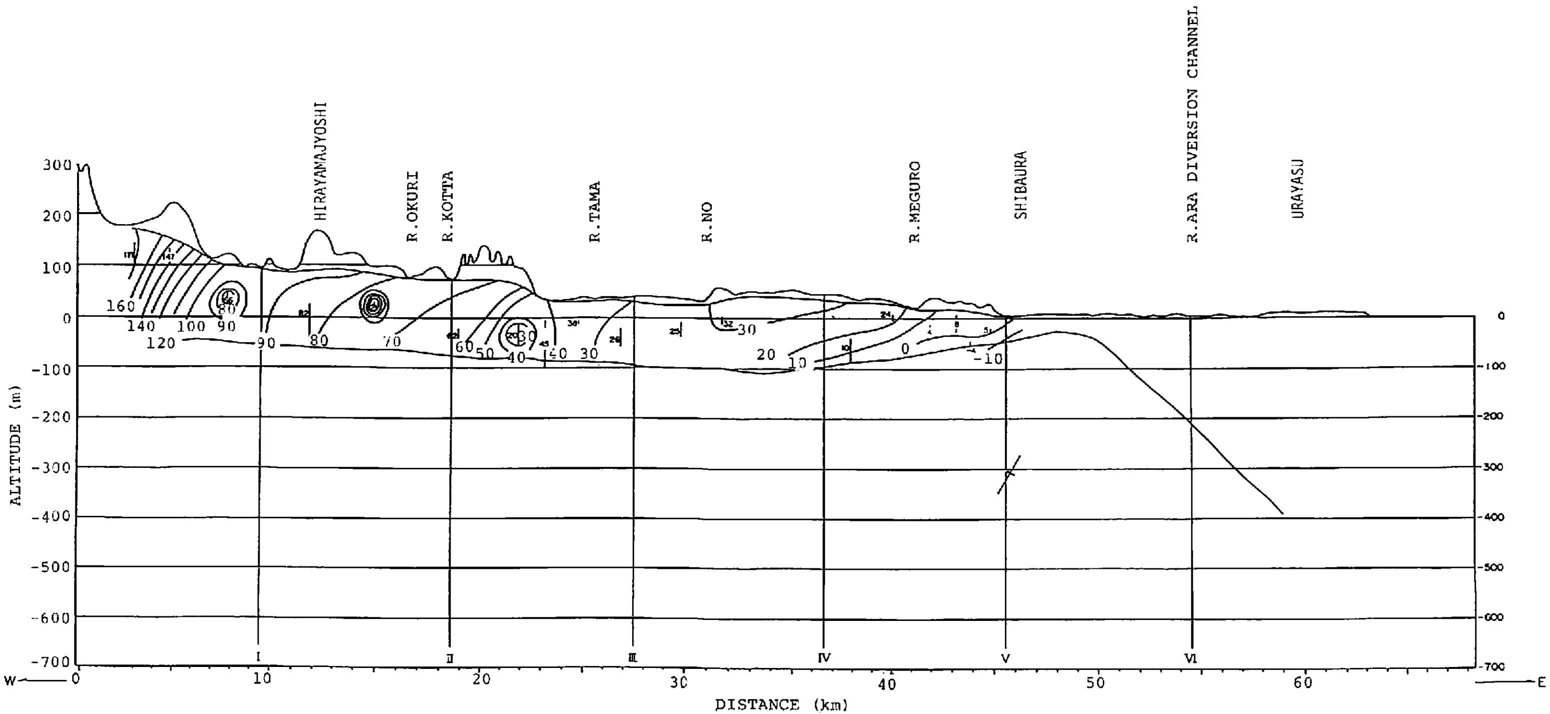

Fig. 17 Same as Fig.13 but for E–E′

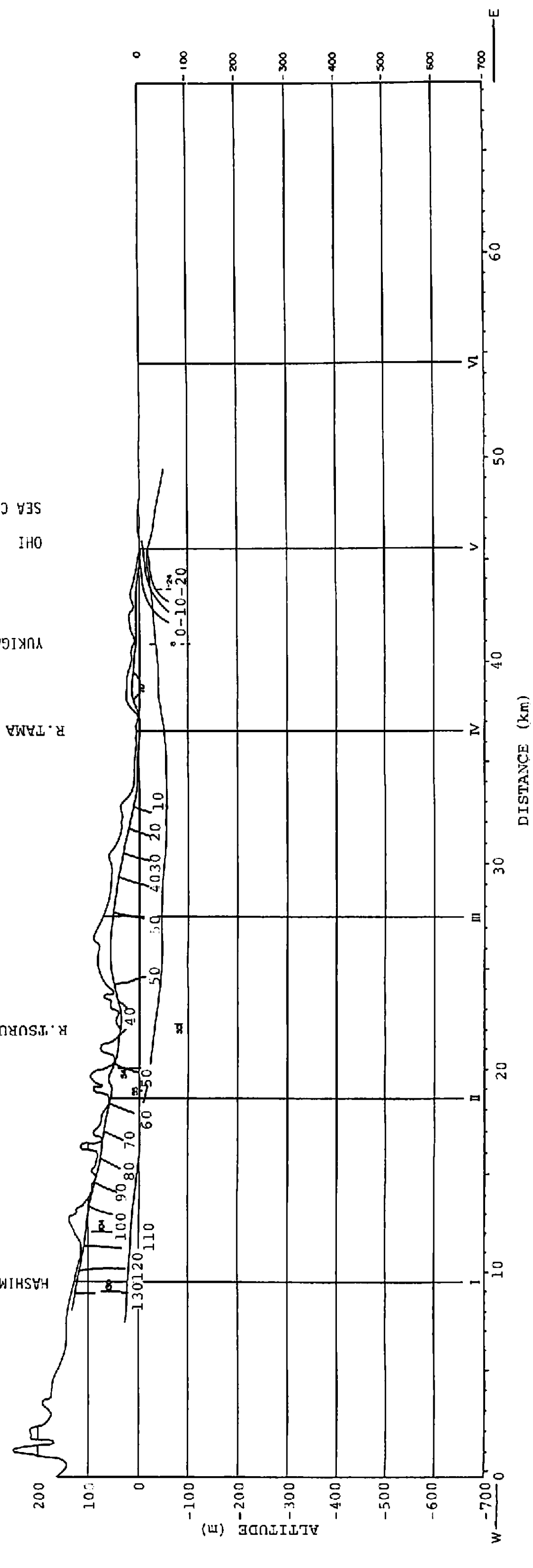

Fig.18 Same as Fig.13 but for F–F′

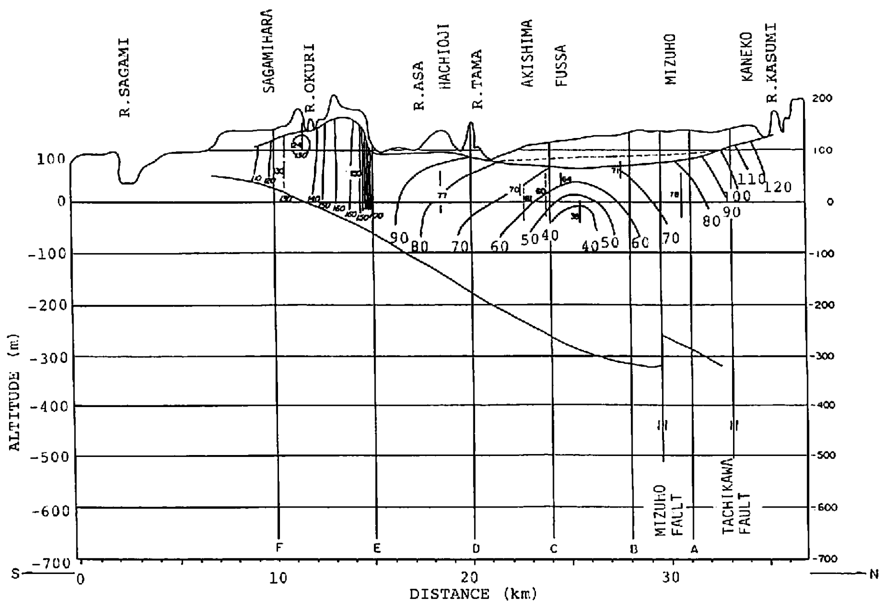

Fig.19 Same as Fig.13 but for I–I′

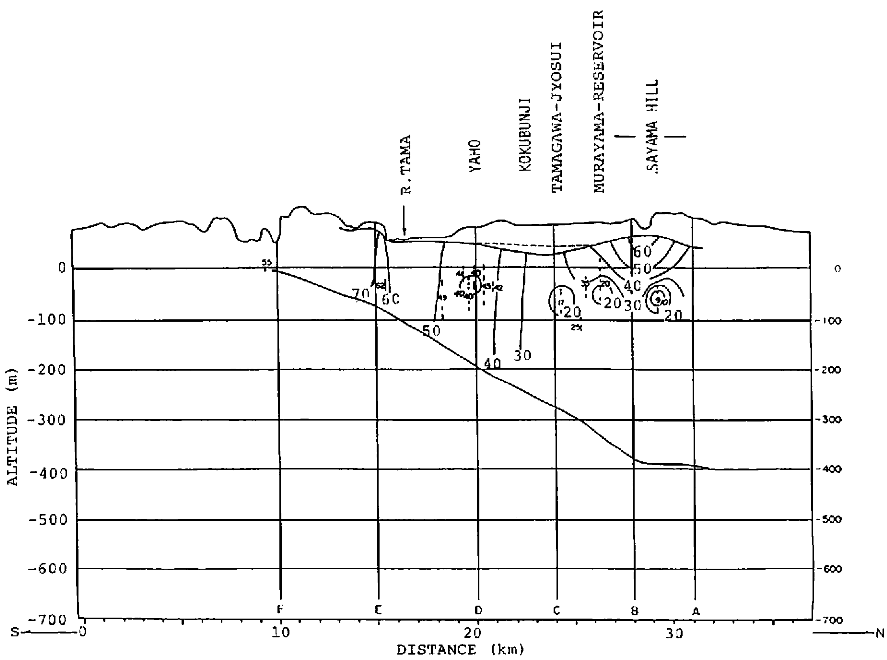

Fig.20 Same as Fig.13 but for II–II′

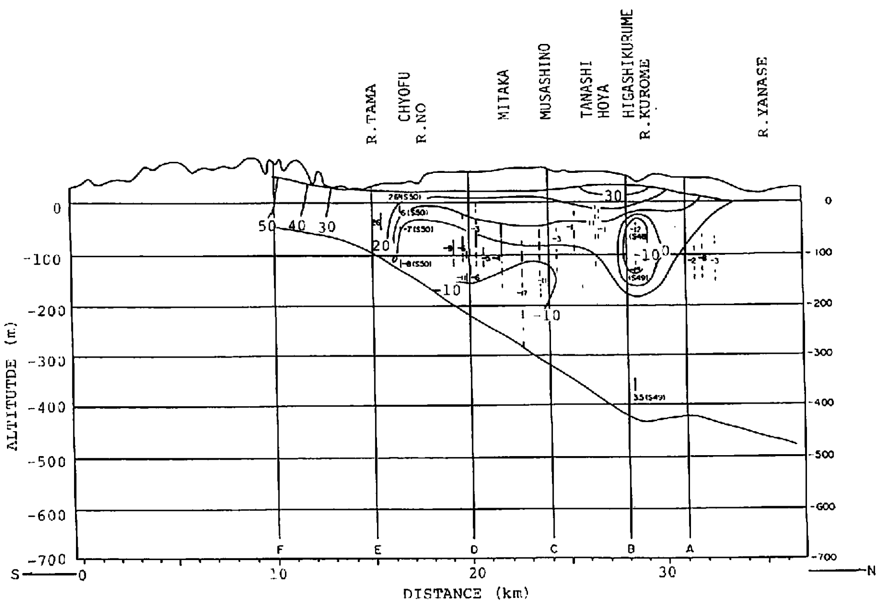

Fig.21 Same as Fig.13 but for III–III′

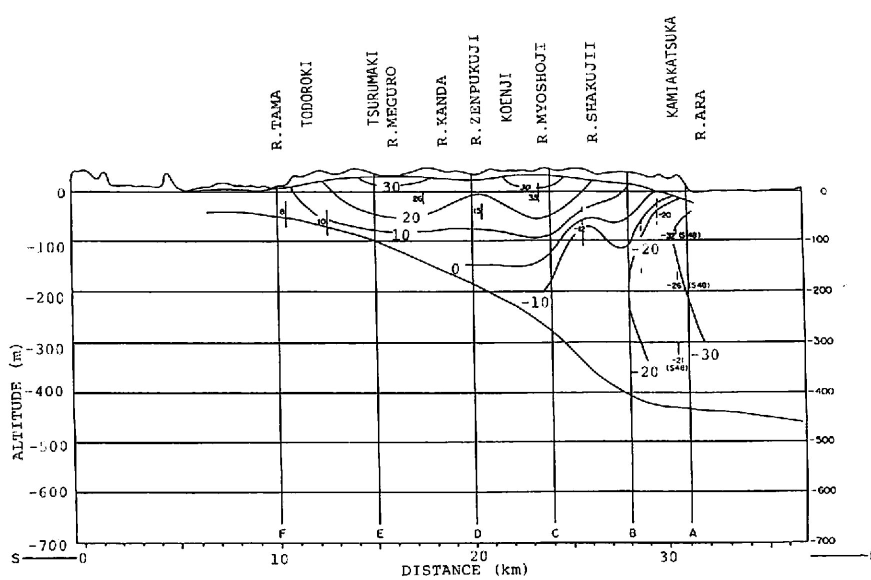

Fig.22 Same as Fig.13 but for IV–IV′

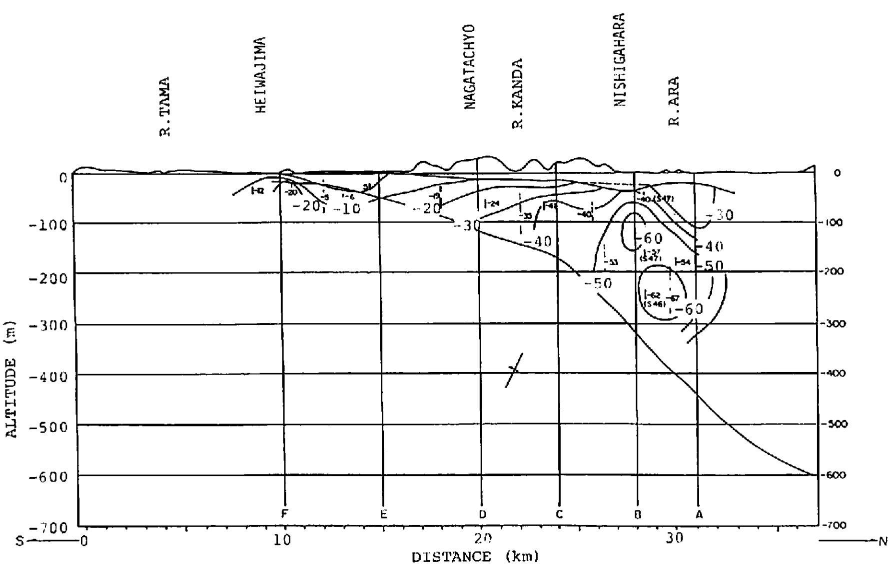

Fig.23 Same as Fig.13 but for V–V′

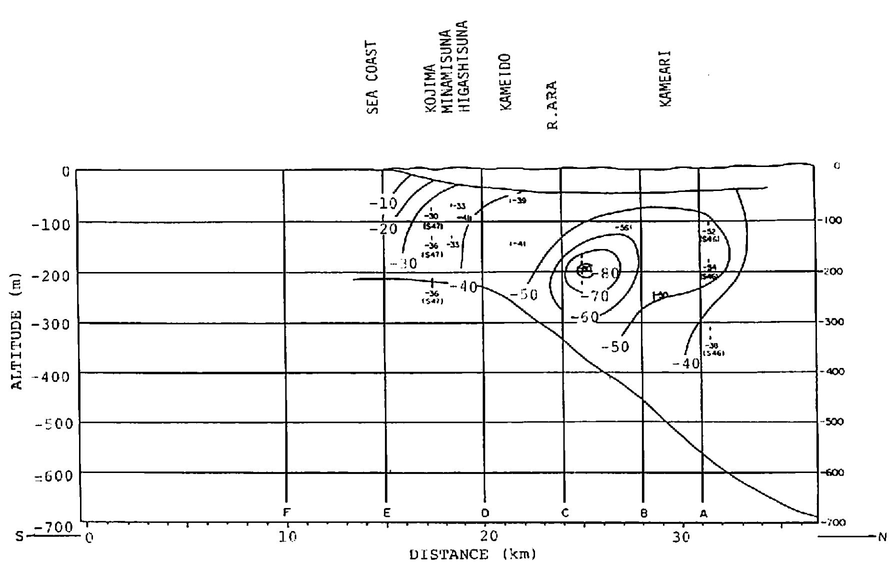

Fig.24 Same as Fig.13 but for VI–VI′

Other features are itemized as follows:

(a) The Tama River acts as a recharge source to groundwater in the reach from Hamura to Chofu.

(b) The groundwater stored in the Tama Hills is also one of the important recharge source to the groundwater withdrawn in the Musashino Upland.

(c) A role of the Sayama Hills as a source of groundwater recharge is not negligible. However, as indicated by the water table by broken lines, available information is not enough to make clear the role. Further investigation is necessary to reveal the groundwater flow from the Sayama Hills to the Musashino Upland.

(d) As shown in Figs.13, 15, and 16 on east-west cross-sections, there are groundwater mound between cross-sections III and IV. Especially in Figs.15 and 16, groundwater flow systems in the upland are separated from the system in the lowland.

(e) As shown in Fig.15, the Tachikawa fault functions to prevent regional-scale groundwater flow from west to east.

3.5 Distribution of the hydraulic head for 1980

Figure 25 through Fig.35 are the distribution map of the hydraulic head for 1980. As a whole, the water table was lowered in the upland and recovered in the lowland. These are results of groundwater development in the upland and prohibition of groundwater withdrawal in the lowland.

All features found in the maps for 1970 are also recognized in 1980. The role of the Tama River (and the Tama Hills) and the Sayama Hills is intensified. The function of the Tachikawa fault to prevent the regional groundwater flow is also strengthened as shown in Figs.26 and 27.

3.6 Distribution of the hydraulic head for 1987

Figure 36 through Fig.46 are the distribution map of the hydraulic head for 1987. As a whole comparing with those for 1980, the water table in the lowland had recovered, but in the upland it had been lowered in some areas though it had recovered in other areas. The Tama River (and the Tama Hills) and the Sayama Hills still act as sources of groundwater recharge and the function of the Tachikawa fault to prevent groundwater flow is recognized.

3.7 Configuration of the water table

Estimated water table configurations for 1970, 1980, and 1987 are shown in Figs.47, 48, and 49, though uncertainty exists in some areas.

Two depressions are found on the water table in Fig.47, one in the lowland and the other in the central part of the upland. The latter position corresponds to the boundary region between Ward District and Tama District. The depression in the upland moved westward in Figs.48 and 49 and a new depression appeared in the western margin of the upland in Fig.49. These features correspond to the regional differences in groundwater use history.

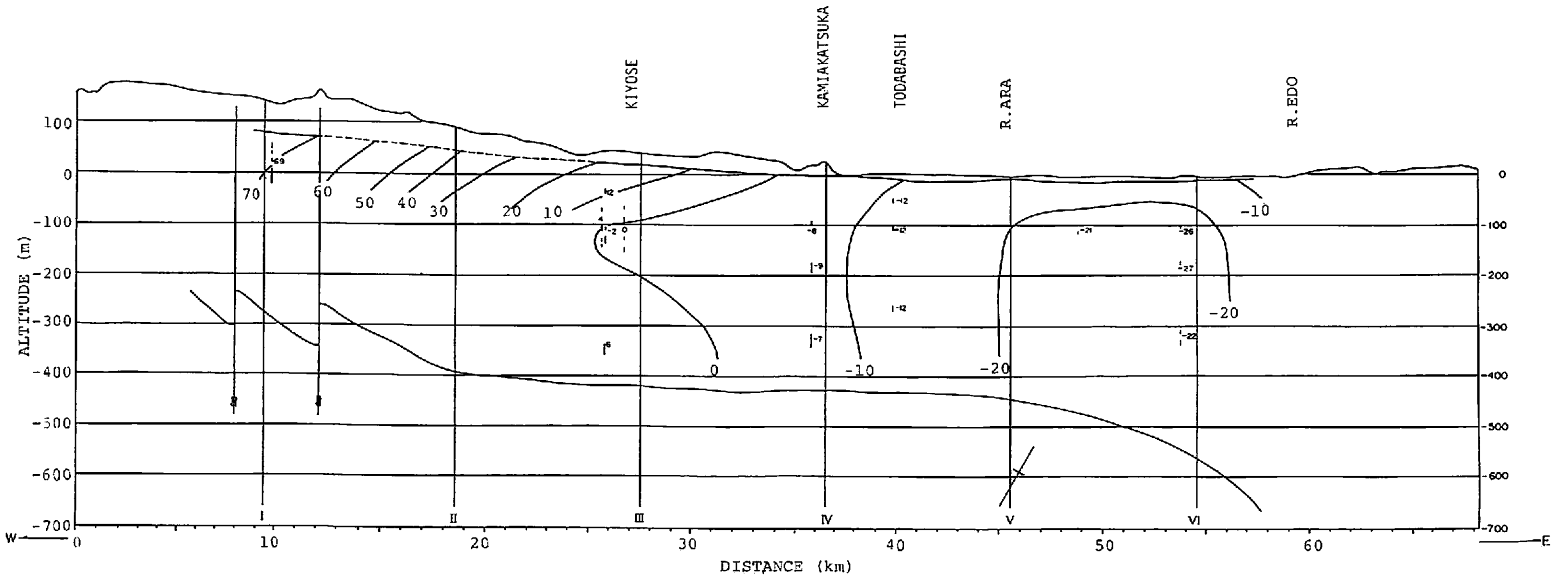

Fig.25 Distribution of the hydraulic head in 1980 on cross-section A–A′

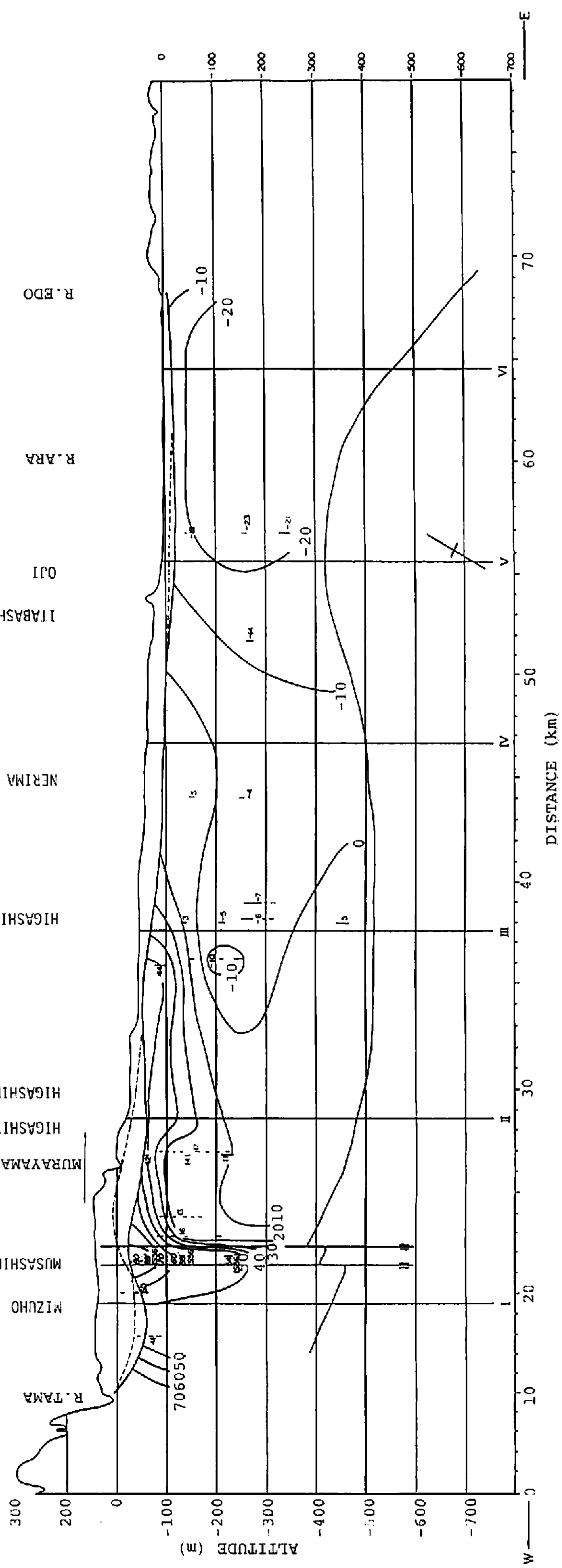

Fig.26 Same as Fig.25 but for B–B′

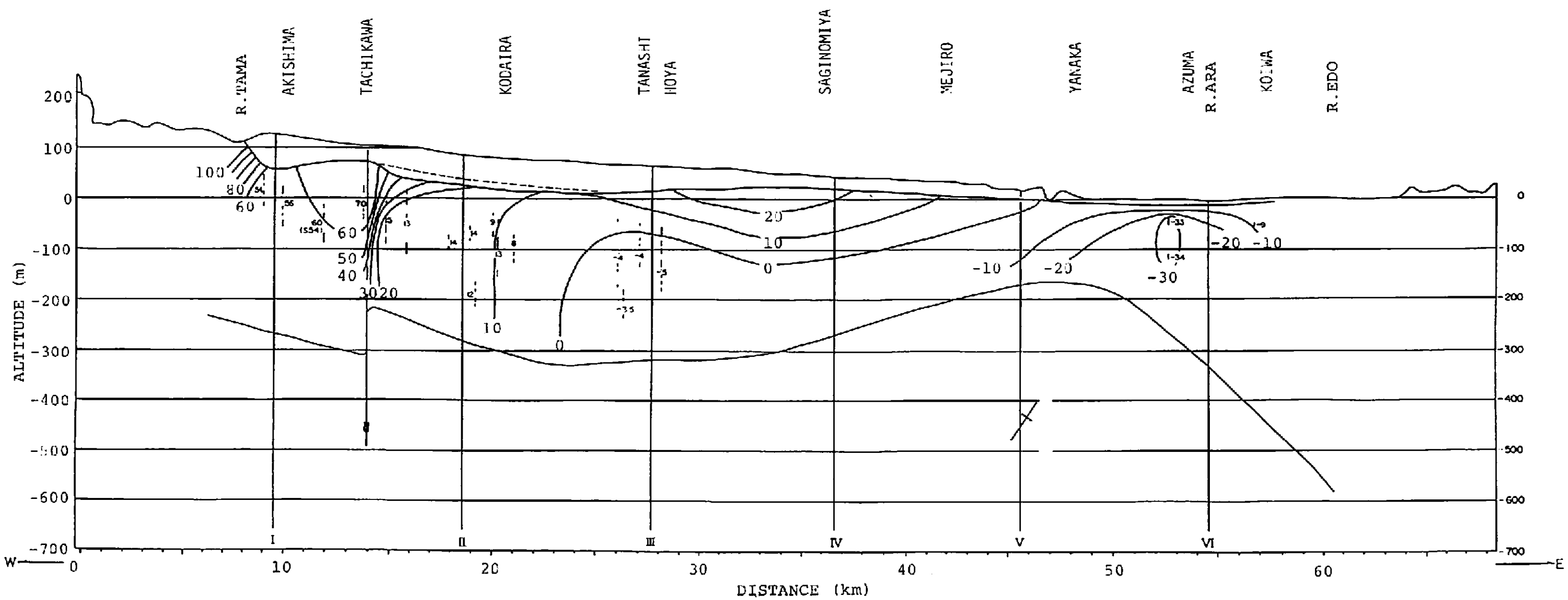

Fig.27 Same as Fig.25 but for C–C'

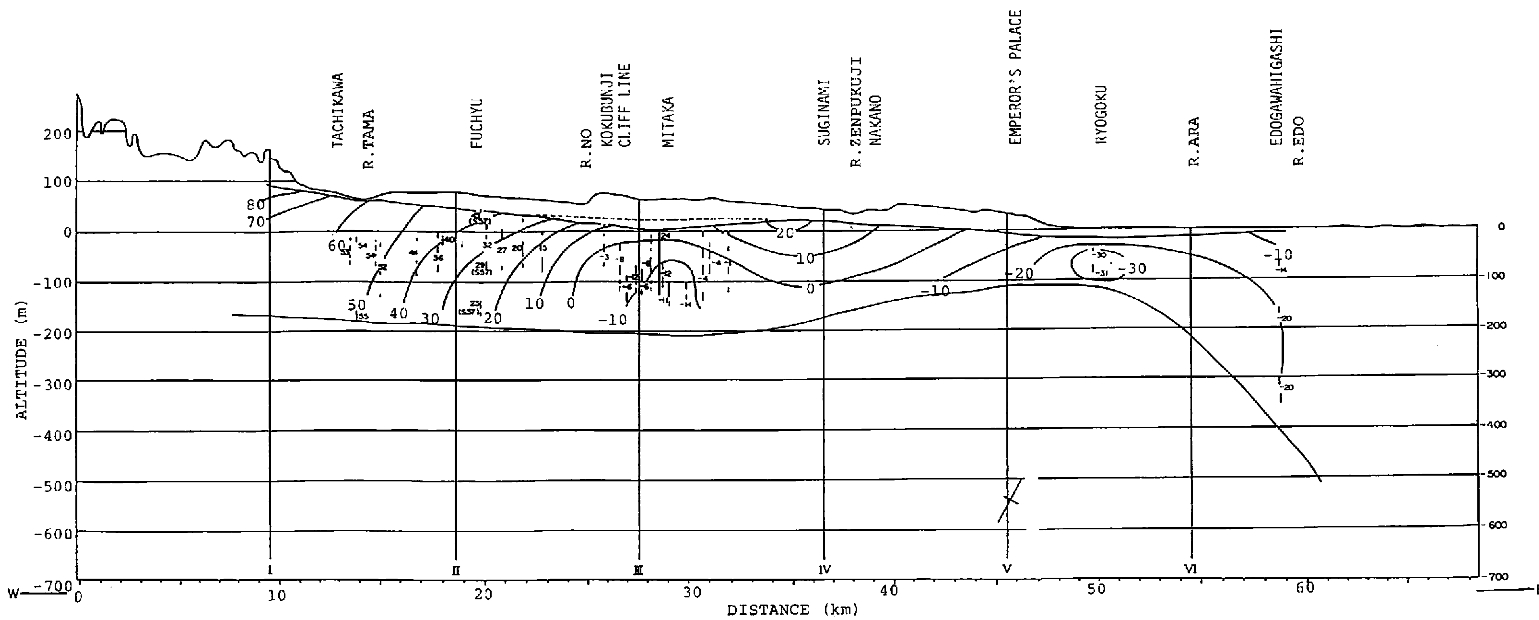

Fig.28 Same as Fig.25 but for D–D′

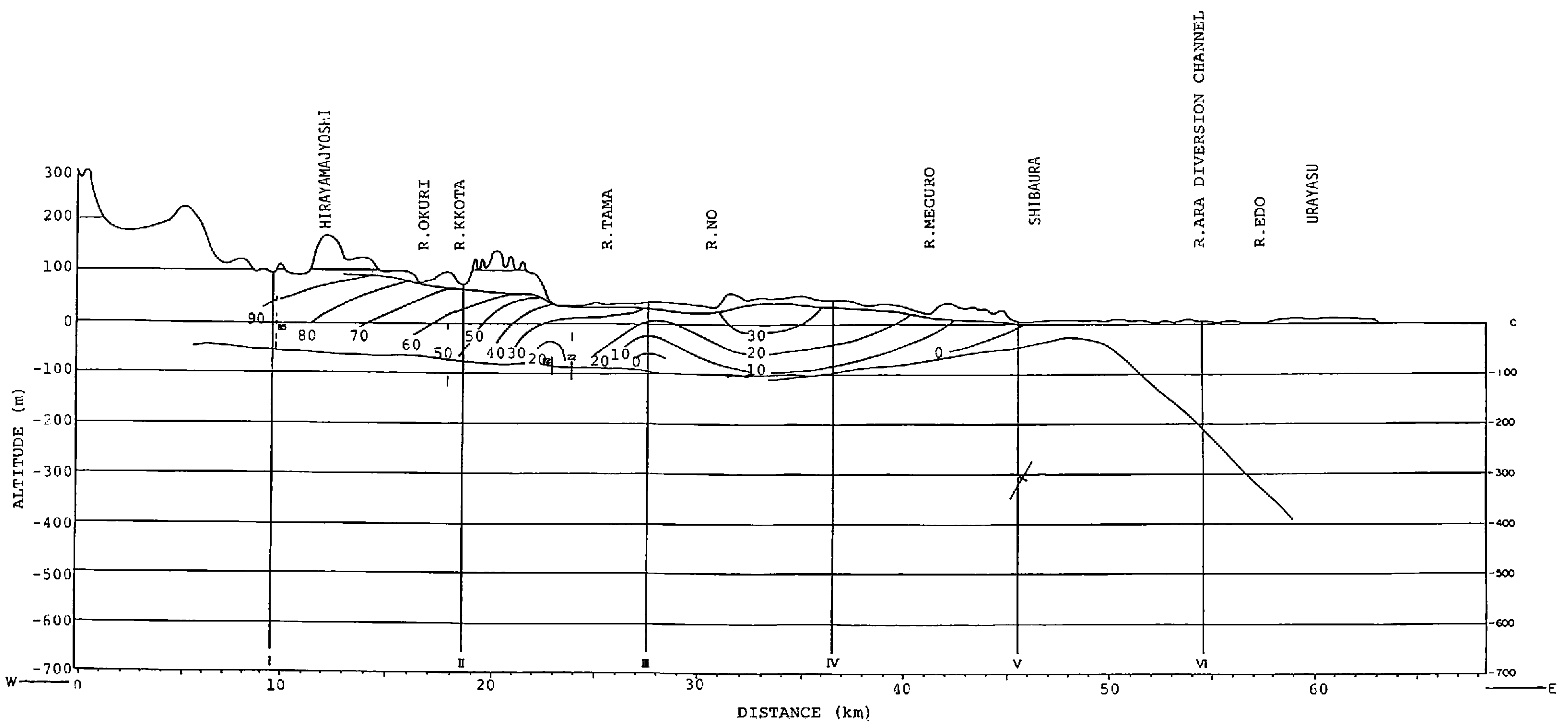

Fig.29 Same as Fig.25 but for E–E′

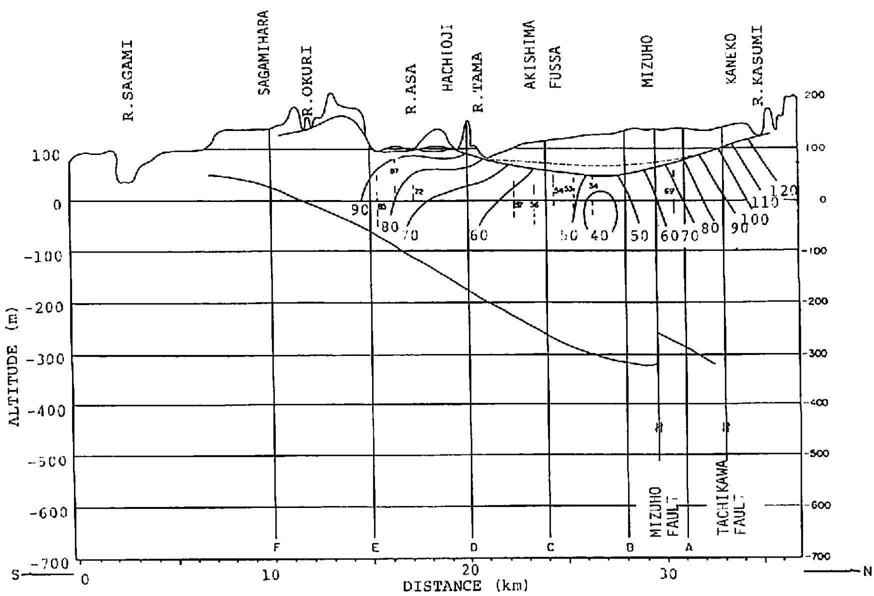

Fig.30 Same as Fig.25 but for I–I′

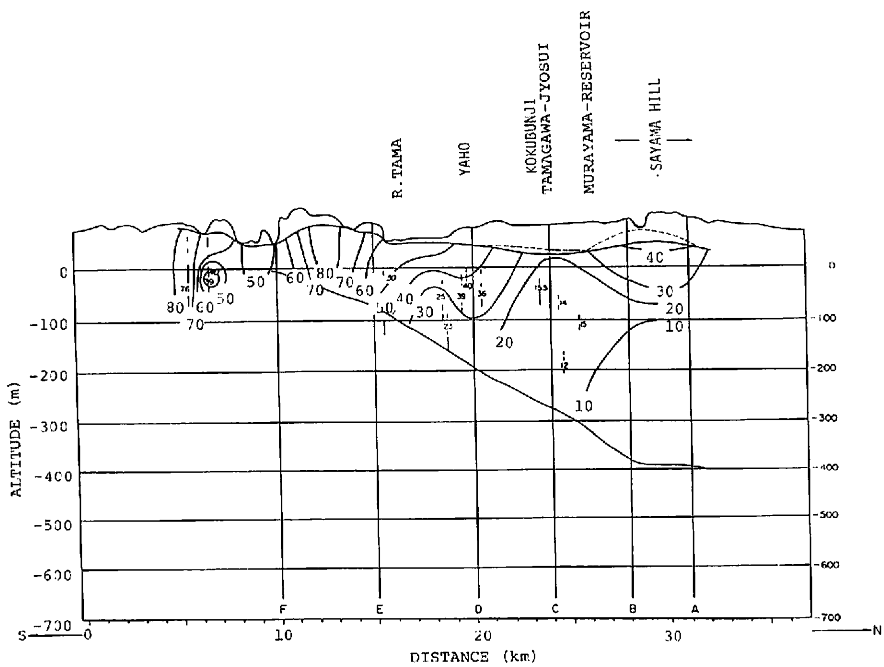

Fig.31 Same as Fig.25 but for II–II′

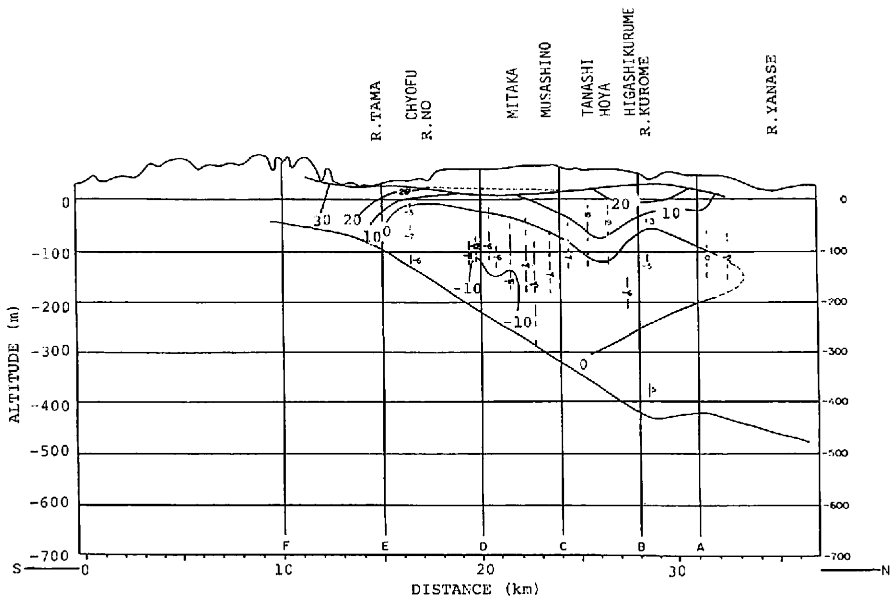

Fig.32 Same as Fig.25 but for III-III′

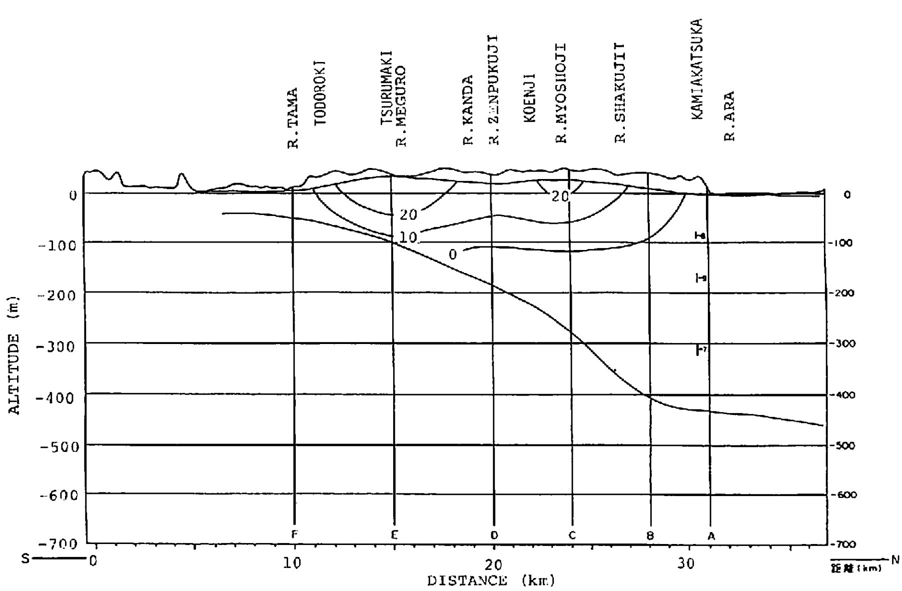

Fig.33 Same as Fig.25 but for IV-IV′

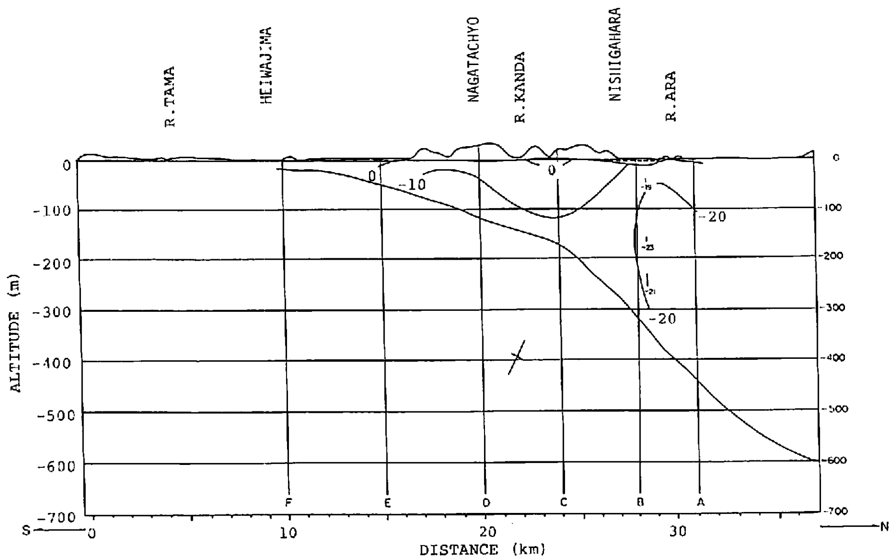

Fig.34 Same as Fig.25 but for V–V′

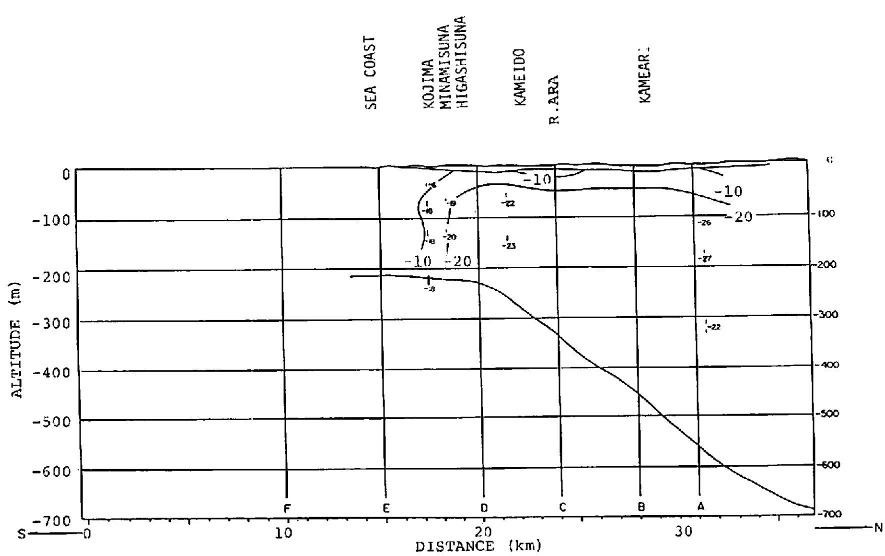

Fig.35 Same as Fig.25 but for VI–VI′

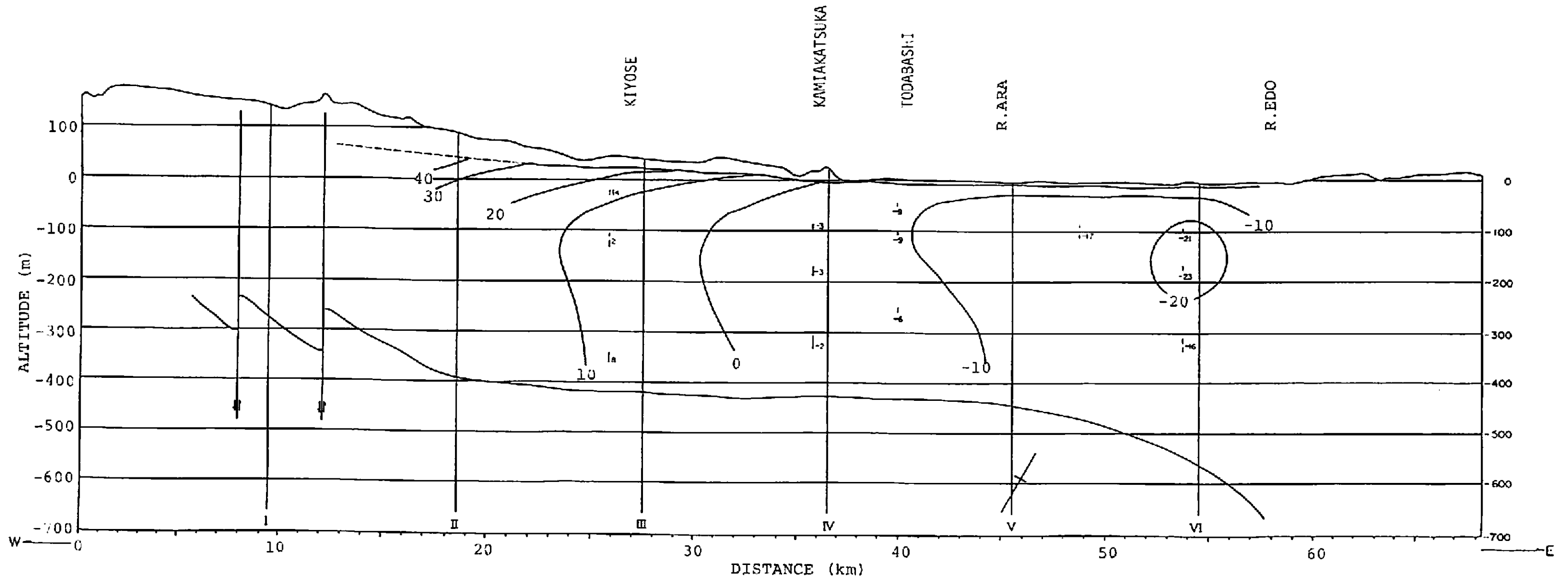

Fig.36 Distribution of the hydraulic head in 1987 on cross-section A–A′

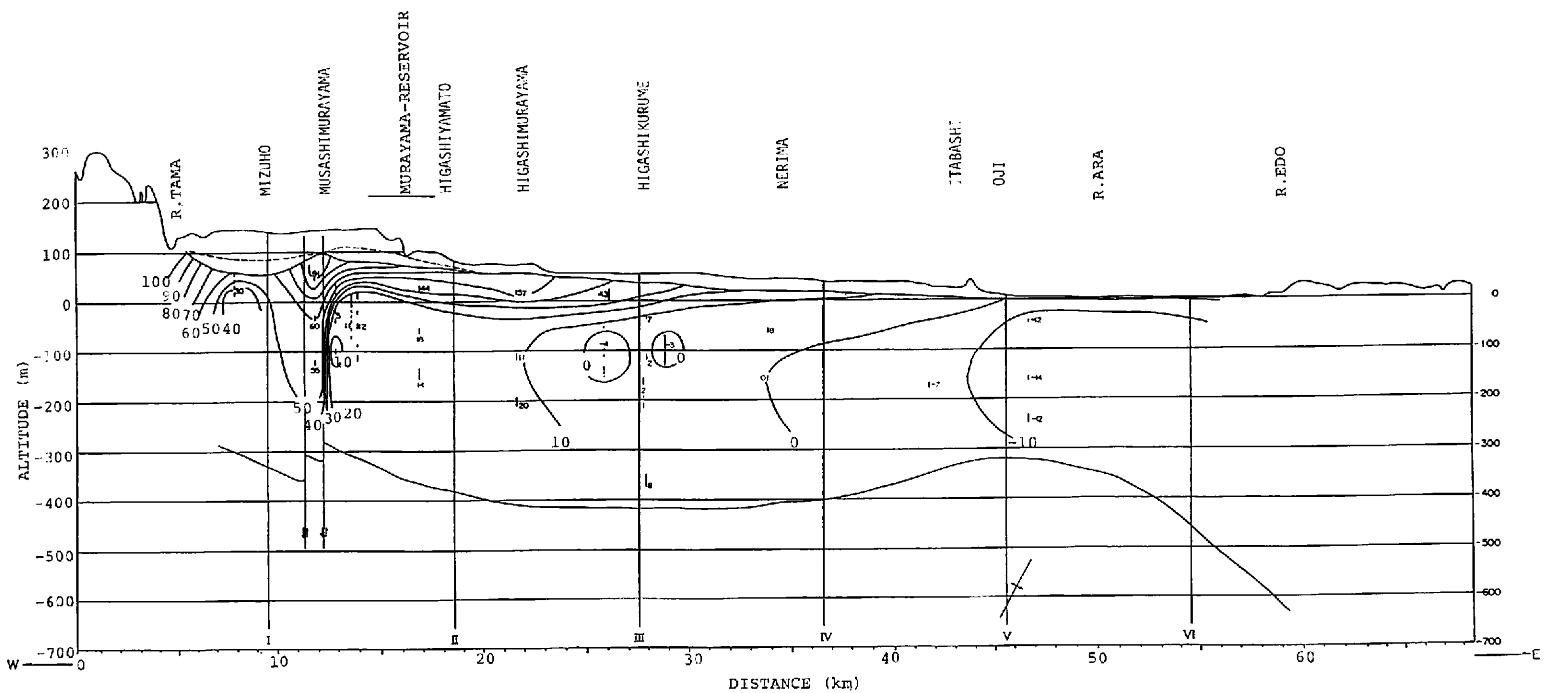

Fig.37 Same as Fig.36 but for B–B′

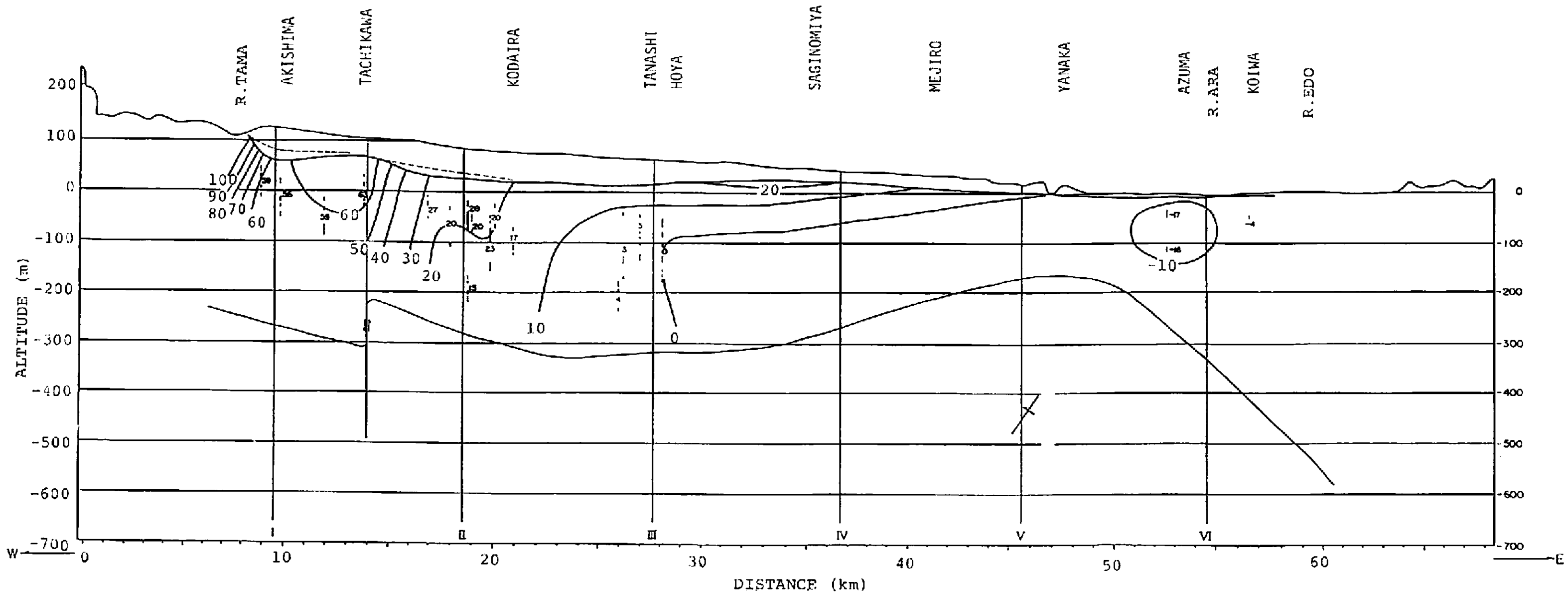

Fig.38 Same as Fig.36 but for C–C′

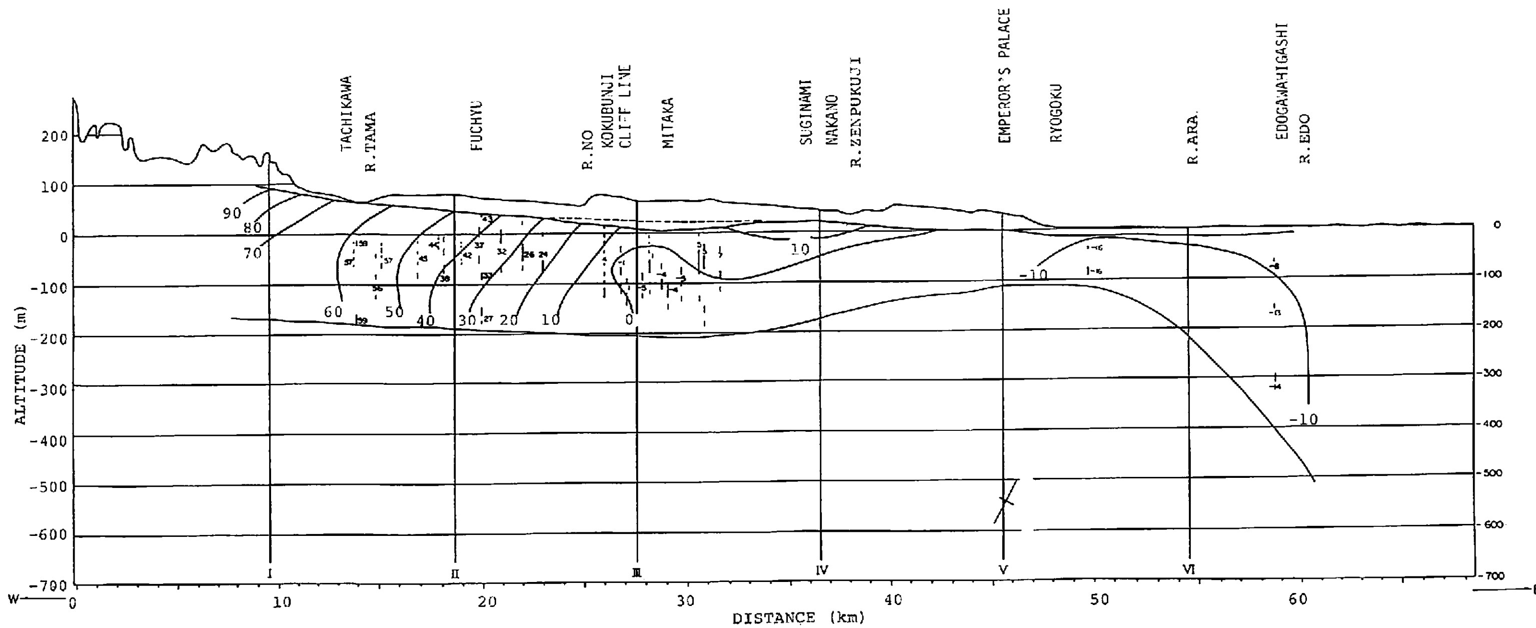

Fig.39 Same as Fig.36 but for D–D′

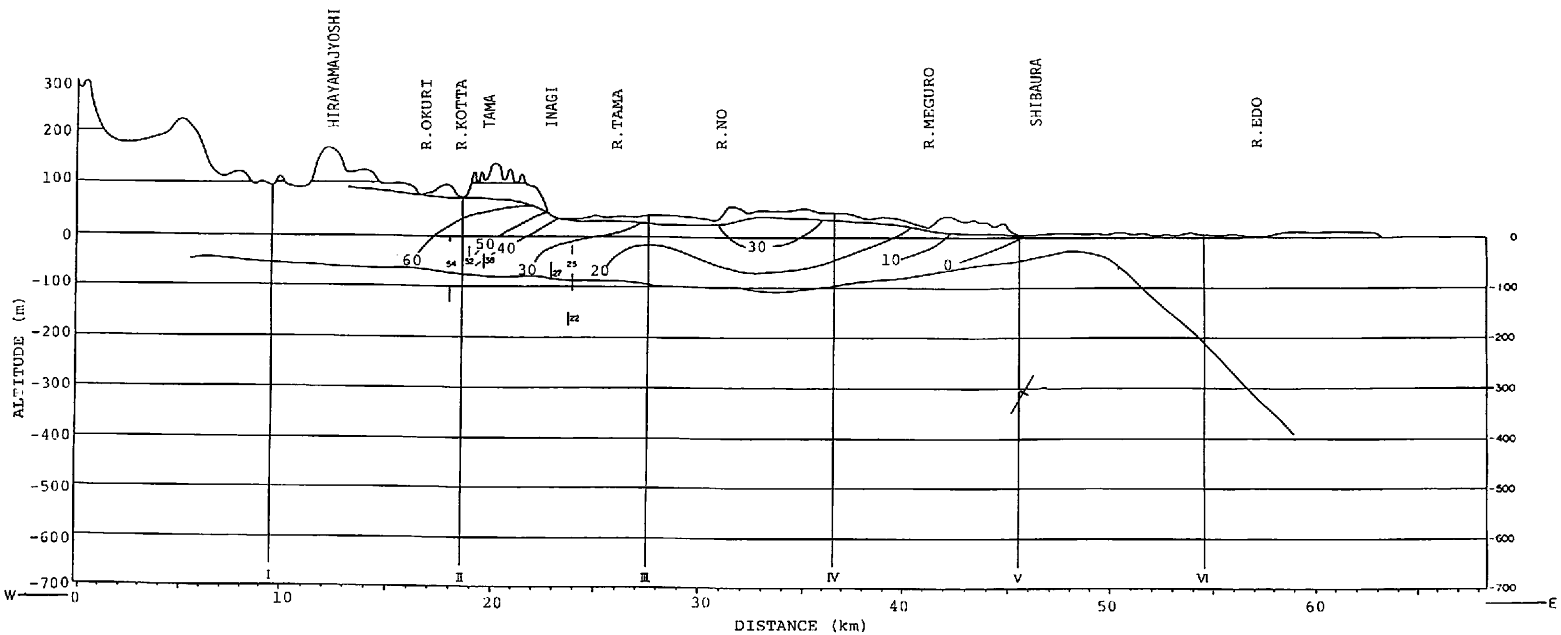

Fig.40 Same as Fig.36 but for E–E′

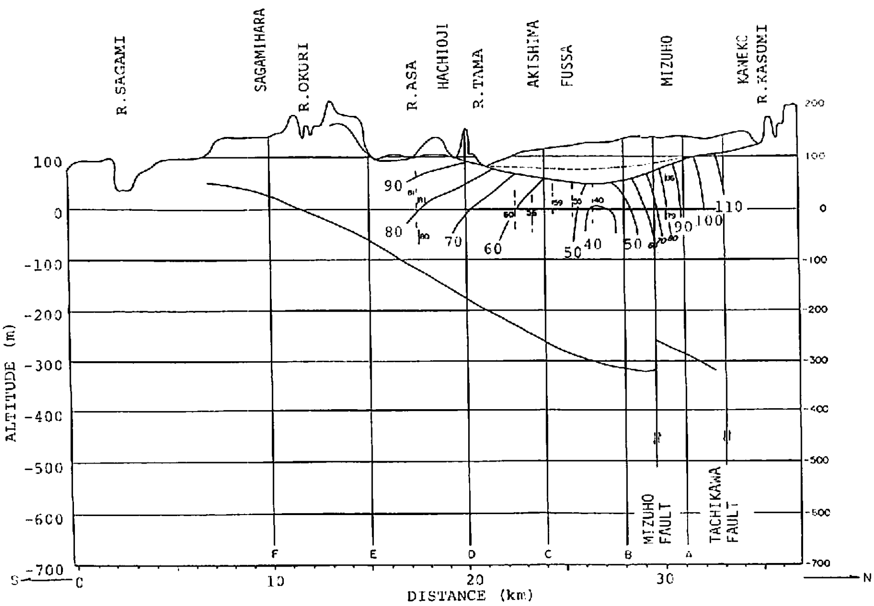

Fig.41 Same as Fig.36 but for I–I′

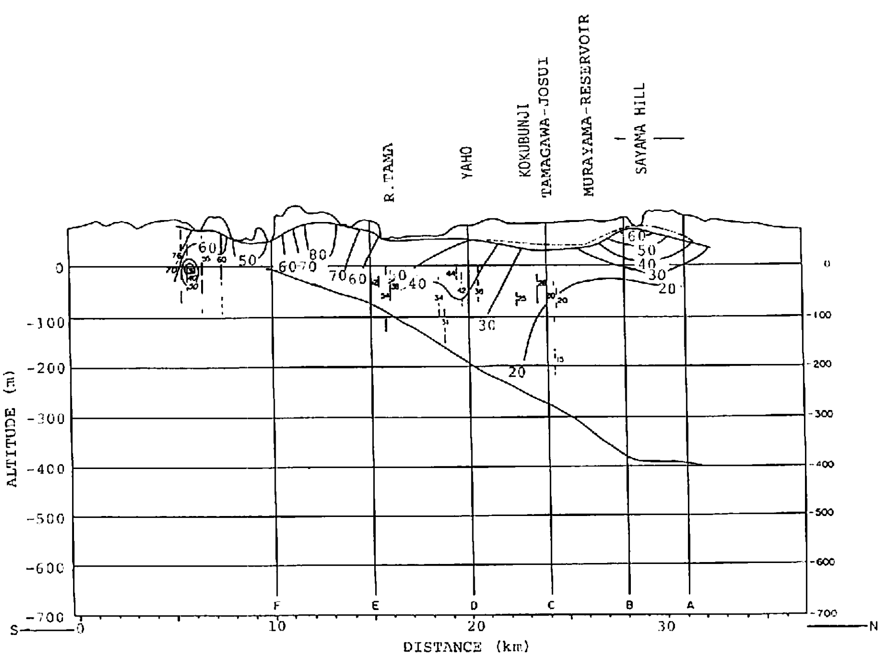

Fig.42 Same as Fig.36 but for II–II′

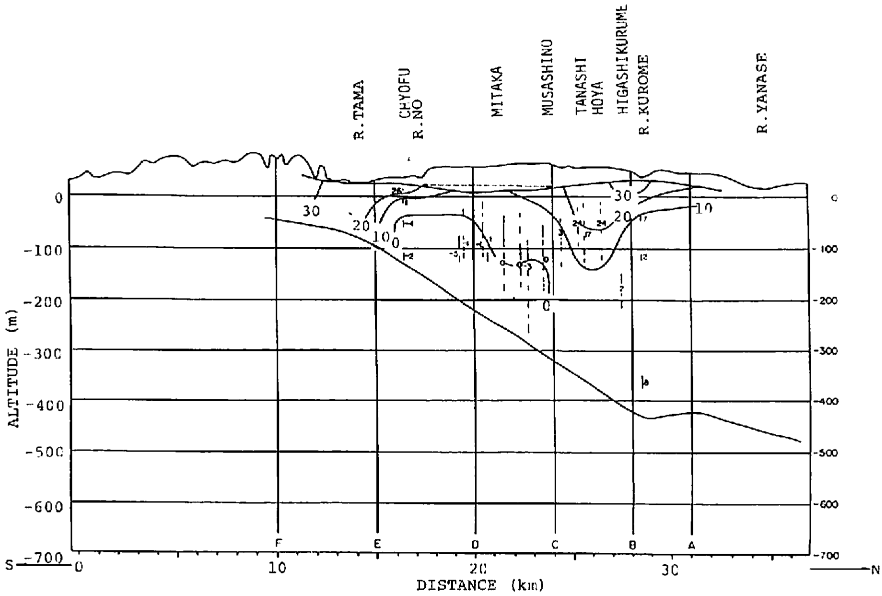

Fig.43 Same as Fig.36 but for III–III′

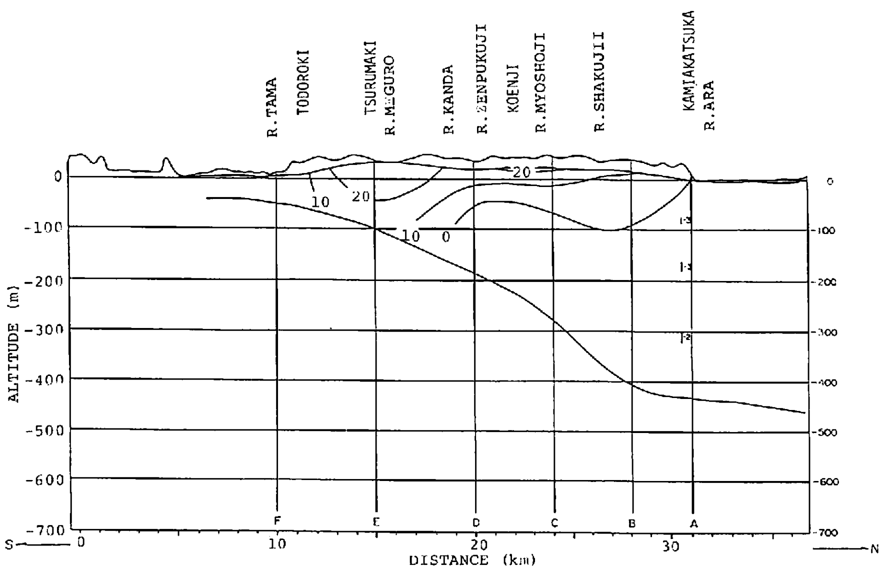

Fig.44 Same as Fig.36 but for IV–IV′

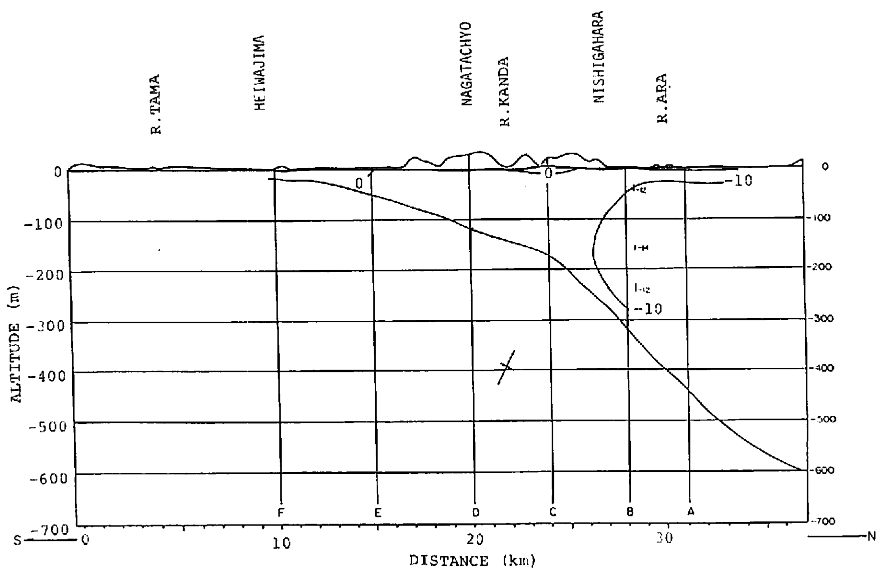

Fig.45 Same as Fig.36 but for V–V′

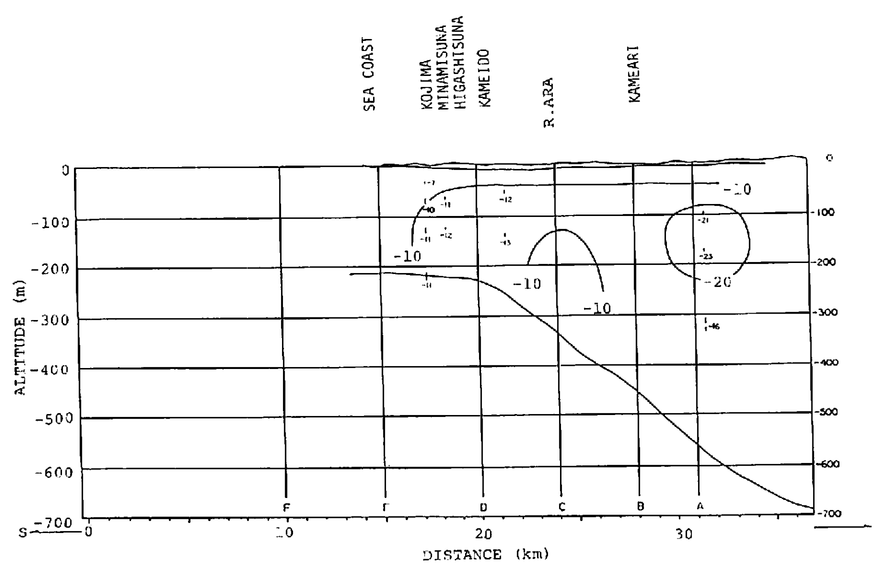

Fig.46 Same as Fig.36 but for VI–VI′

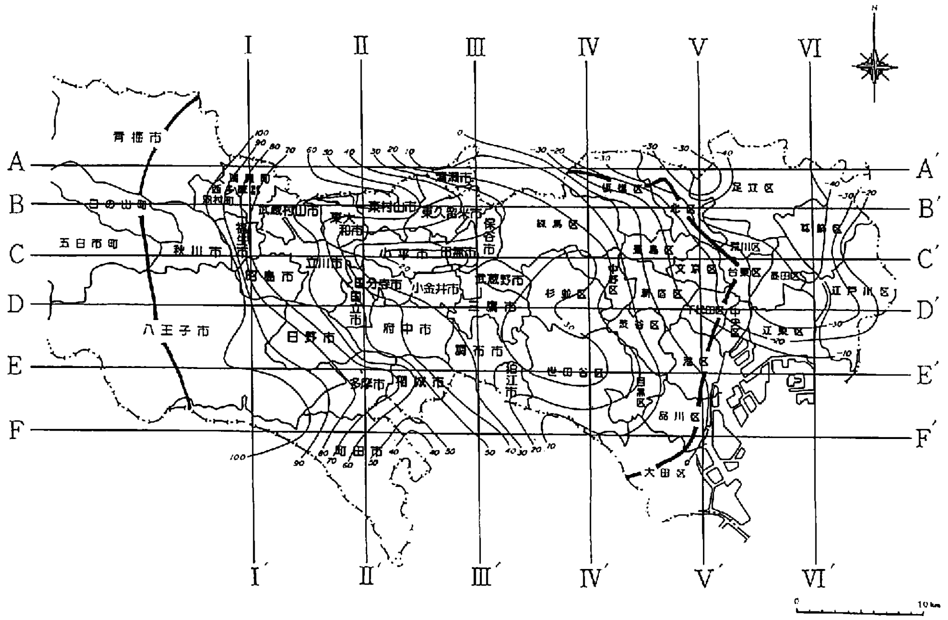

Fig.47 Estimated water table configuration for 1970

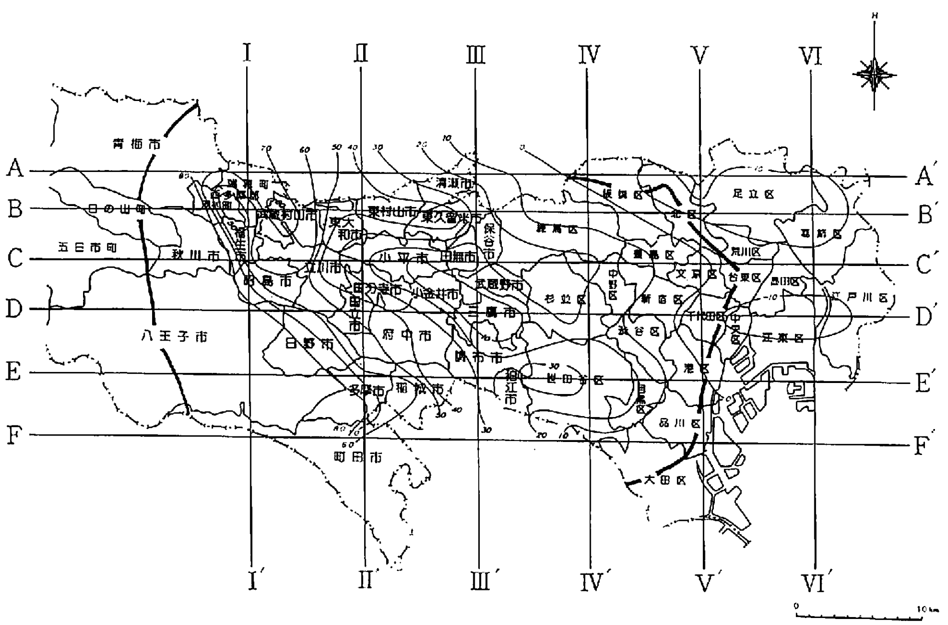

Fig.48 Same as Fig.47 but for 1980

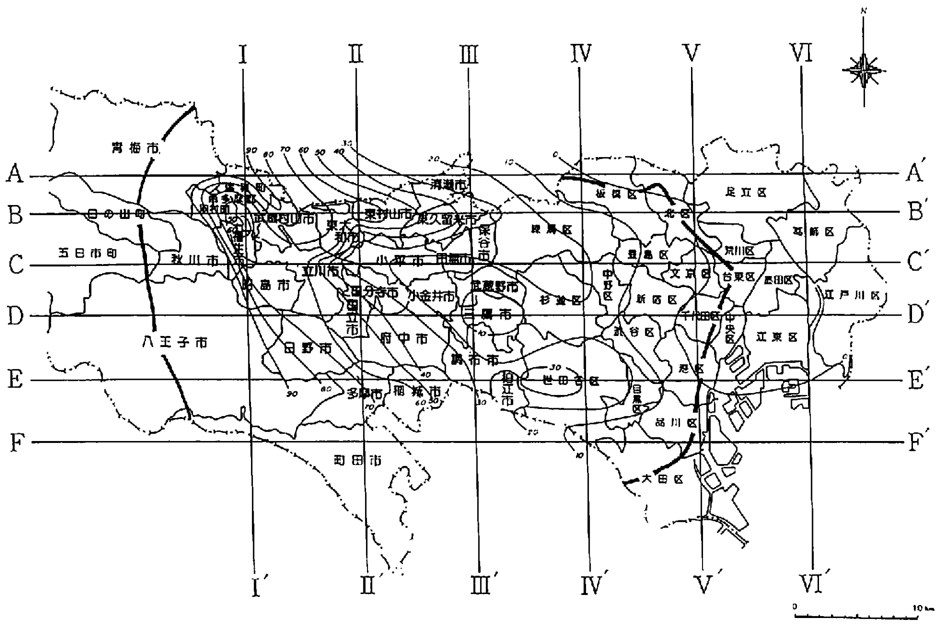

Fig.49 Same as Fig.47 but for 1987

CONCLUSIONS

1) The aquifer-aquitard system in the lowland and upland in Tokyo Metropolitan area had been under great stress due to groundwater withdrawal after the second World War. The stress had resulted in one of the most severe land subsidence in the world.

2) Groundwater management policy adopted by Tokyo Metropolice succeeded in stopping the land subsidence in the lowland by prohibiting groundwater withdrawal, but groundwater is still in use in the upland area.

3) Temporal changes of the regional-scale groundwater flow pattern in three-dimensional space were made clear by constructing the distribution map of the hydraulic head on two-dimensional vertical cross-sections for years 1970, 1980, and 1987.

4) From the revealed pattern of regional groundwater flow, roles of Tama and Sayama hills and the Tama River as groundwater recharge source, the function of Tachikawa fault in preventing groundwater flow, and areal differences in the response of aquifer-aquitard system to regulation and prohibition of groundwater withdrawal were made clear.

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