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Management of groundwater in the Nobi Plain that modeled groundwater use for earthquake disasters and environmental preservation

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Abstract. The pumped discharge of groundwater increased rapidly in Japan during the period of fast economic growth since the beginning of the 1960s. As a result, land subsidence has been observed, including throughout the Nobi Plain. Laws have led to restrictions on the collection of underground water, and pumped discharge has gradually reduced. In recent years, the groundwater level that had formerly decreased has begun to rise again, leading to less land subsidence. However, as groundwater levels rise, the occurrence of new problems is feared, such as the danger posed by liquefaction. In this study, an analysis was conducted on the changes in the state of groundwater based on future groundwater-use scenarios and forecasts of land subsidence. This involved thinking about the effective use of groundwater to prevent excessive rises in groundwater levels, using a three-dimensional groundwater-flow analysis and a perpendicular one-dimensional subsidence consolidation analysis. As a result, it was shown that it would be beneficial to use groundwater as a means of continuous environmental preservation and as the water resource at the earthquake disaster. At this time new wells were set up at the refuge of the disaster specified in the Nobi Plain. And the remarkable land subsidence was not caused by pumped discharge.

1 Introduction

Groundwater has been used for various purposes and has long been a valuable water resource in Japan. Although groundwater has been used for a long time by many people, the pumped discharge of groundwater increased rapidly during the period of high economic growth experienced since the beginning of the 1960s. This was also true in the Nobi Plain, where abundant groundwater was extracted for use in industries such as the steel industry. As a result, groundwater was extracted from almost the entire area, and subsidence of the plains was observed. The pumped discharge was gradually reduced by restrictions on groundwater collection enforced both in law and the local ordinances. In recent years, the groundwater level has begun to increase again, and the occurrence of subsidence has simultaneously started to decrease. However, because of the rising groundwater levels, the occurrence of new problems, such as liquefaction, is feared.

This study aimed to propose ways to manage large-scale groundwater management by investigating groundwater state changes based on future groundwater-use scenarios. It also aimed to forecast changes in the ground by thinking about the effective use of groundwater to prevent groundwater levels rising excessively by using three-dimensional groundwater-flow analysis and perpendicular one-dimensional consolidation subsidence analysis.

2 Effective use of groundwater

Groundwater offers various advantages. Changes in the temperature of groundwater are small. Groundwater can be easily accessed by digging wells. Safe, delicious groundwater has become more easily available in recent years as groundwater pumping technology and film filtration technology have developed. Groundwater is used in municipal water supplies, as familiar water in the parks using spring water and measures of a heat island and for improving water quality by discharging it to rivers and ponds. Moreover, groundwater is highly valuable as a water resource to supply water following a disaster. The well water at schools and parks where there had been limited earthquake damage was used as drinking water and as water for daily life in refuges, in place of water from waterworks that were out of action because the water supply had been cut off following the Great Hanshin-Awaji Earthquake Disaster in 1995. It is feared that another great earthquake will occur in the near future. When this great earthquake occurs, water shortages are expected because there will be interruptions to water supply networks. To model this, the following conditions were assumed in this study. After a disaster such as the Tokai earthquake occurs, wells are set up in the refuges of each municipality. Pumped groundwater is usually used for both waterworks and environmental water as well as being used for drinking water and daily life in the disaster zone.

3 Groundwater-flow analysis and consolidation analysis

The changes in groundwater state when new wells were established in refuges was predicted based on a three-dimensional groundwater-flow analysis of the Nobi Plain (Yasuhiro et al., 2005). The area covered by the analysis was 1164 km^2 and includes most of the Nobi Plain, as shown in Fig. 1. In the analysis, it was assumed that a new well was established in each refuge that was within the area analyzed. Figure 2 shows the distribution of the refuges in the area analyzed. Once set up, the wells were in continuous operation, and it is assumed that the pumped groundwater is usually used as environmental water but is also used as water for daily life during a disaster. It was assumed that these wells began operating in 2008. In this analytical area, there was a total of 1663 refuges set up by municipalities during times of disaster. The pump discharge in each well was based on the amount of the water supply per person that was the volume of water of the target of the emergency water supply at the disaster in the city of Nagoya. The assumed amounts of water supplied were $3\,L\,d^{-1}$ (Case 1), $20\,L\,d^{-1}$ (Case 2), $100\,L\,d^{-1}$ (Case 3) and $250\,L\,d^{-1}$ (Case 4). Table 1 shows the number of evacuees in each refuge (the population of each municipality divided by the number of refuges). Moreover, the pumped groundwater per person of each case multiplied the number of evacuees in each refuge and the amount of groundwater pumped in a place in each refuge were calculated. The amount of the pumped groundwater after the new wells had operated was calculated. The amount of the pumped groundwater from new wells was added to that amount of the existing pumped groundwater. Table 2 shows the amount of groundwater pumped after the well had been operating. The ground-level change in each case in the vicinity of Jushiyama observation well, shown in Fig. 1, where remarkable levels of subsidence had been observed in the past, was predicted based on the perpendicular one-dimensional

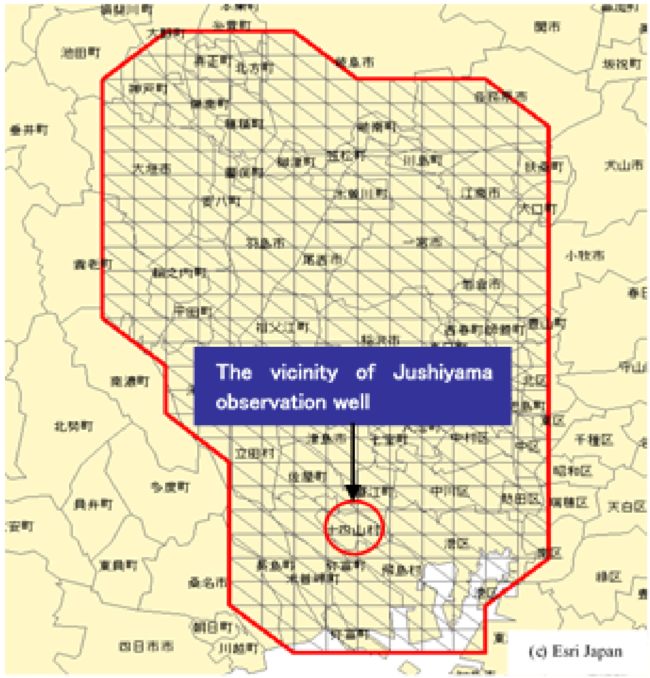

Figure 1. Analysis area.

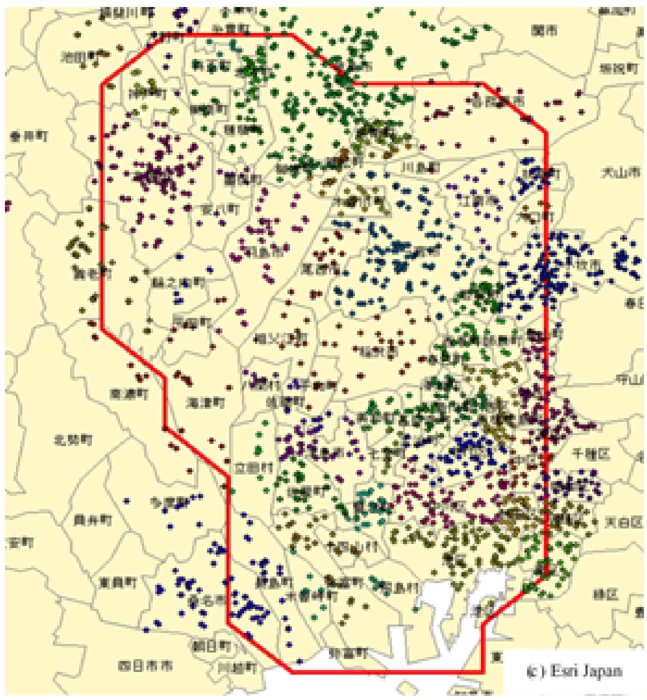

Figure 2. Analysis area and distribution of refuges.

consolidation subsidence analysis of the Nobi Plain (Kenji et al., 1992).

Table 1. Number of evacuees in each place.

Municipality name	Number of refuges	Number of evacuees per place
District of Atsuta	27	2307
District of Kita	31	3324
District of Showa	6	3285
District of Nakagawa	71	3076
District of Naka	19	3804
District of Nakamura	48	2812
District of Nishi	50	2872
District of Higashi	8	2601
District of Mizuho	5	3642
District of Minato	74	2026
District of Minami	19	2854
City of Aisai	65	1032
City of Ichinomiya	173	2209
City of Inazawa	41	3379
City of Iwakura	40	1188
Town of Oguchi	6	3097
Town of Oharu	13	2270
Town of Kanie	28	1263
Town of Kisozaki	7	848
City of Kitanagoya	29	2872
City of Kiyosu	37	1534
City of Konan	20	5081
City of Komaki	55	1126
Town of Shippo	12	1935
Town of Jimokuji	23	1744
City of Tsushima	39	1711
Village of Tobishima	8	559
Town of Toyoyama	13	1002
Town of Haruhi	10	776
Town of Fuso	18	1446
Town of Miwa	14	1744
City of Yatomi	34	1339
Town of Anpachi	7	2197
Town of Ikeda	2	1643
City of Ogaki	106	1357
Town of Ono	4	940
City of Kaizu	19	1255
City of Kakamigahara	23	4372
Town of Kasamatsu	28	841
Town of Kitagata	30	600
Town of Ginan	44	518
City of Gifu	175	1406
Town of Godo	20	1019
City of Hashima	50	1379
City of Mizuho	26	1859
City of Motosu	13	1218
Town of Yoro	18	726
Town of Wanouchi	9	1075
City of Kuwana	46	1609
Total	1624	

Table 2. Amount of groundwater pumped in the refuges in each municipality.

Municipality name	Amount of groundwater pumped per place ($m^3\,yr^{-1}$)			
	Case 1	Case 2	Case 3	Case 4
District of Nishi	3145	20 969	104 846	262 114
District of Minato	2218	14 788	73 941	184 853
District of Showa	3597	23 978	119 891	299 728
District of Minami	3125	20 836	104 181	260 453
District of Kita	3640	24 266	121 330	303 326
District of Naka	4166	27 770	138 852	347 129
District of Nakagawa	3369	22 458	112 289	280 724
District of Higashi	2848	18 984	94 922	237 304
District of Atsuta	2594	17 299	86 497	216 242
District of Nakamura	3079	20 529	102 646	256 616
District of Mizuho	3988	26 590	132 949	332 373
City of Komaki	1233	8217	41 085	102 711
City of Ichinomiya	2419	16 124	80 622	201 555
City of Kitanagoya	3145	20 965	104 827	262 067
City of Aisai	1130	7533	37 664	94 159
City of Kiyosu	1679	11 196	55 980	139 950
City of Tsushima	1873	12 487	62 435	156 087
City of Konan	5563	37 089	185 444	463 609
City of Yatomi	1466	9772	48 860	122 151
Town of Fuso	1583	10 553	52 766	131 916
City of Iwakura	1301	8673	43 366	108 414
Town of Oharu	2486	16 573	82 863	207 159
Town of Oguchi	3391	22 606	113 030	282 575
Town of Shippo	2119	14 125	70 624	176 561
Town of Kanie	1383	9220	46 101	115 252
Town of Miwa	1909	12 730	63 648	159 120
Town of Jimokuji	1910	12 733	63 666	159 164
Town of Toyoyama	1098	7317	36 584	91 461
City of Inazawa	3700	24 669	123 345	308 363
Town of Haruhi	849	5663	28 313	70 783
Village of Tobishima	612	4083	20 413	51 032
City of Gifu	1539	10 260	51 302	128 254
City of Ogaki	1488	9908	49 542	123 856
City of Kakamigahara	4788	31 918	159 589	398 972
City of Kuwana	1761	11 742	58 710	146 776
City of Hashima	1509	10 063	50 315	125 788
City of Mizuho	2036	13 572	67 859	169 648
City of Kaizu	1375	9164	45 818	114 544
City of Motosu	1334	8894	44 470	111 174
Town of Yoro	795	5302	26 509	66 273
Town of Ikeda	1799	11 996	59 982	149 954
Town of Ono	1030	6864	34 320	85 800
Town of Ginan	567	3782	18 912	47 280
Town of Kasamatsu	920	6136	30 682	76 704
Town of Godo	1116	7439	37 194	92 984
Town of Kitagata	656	4377	21 883	54 707
Town of Kisozaki	929	6193	30 966	77 414
Town of Wanouchi	1177	7844	39 221	98 053
Town of Anpachi	2406	16 040	80 201	200 502
Total	103 843	692 289	3 461 455	8 653 634

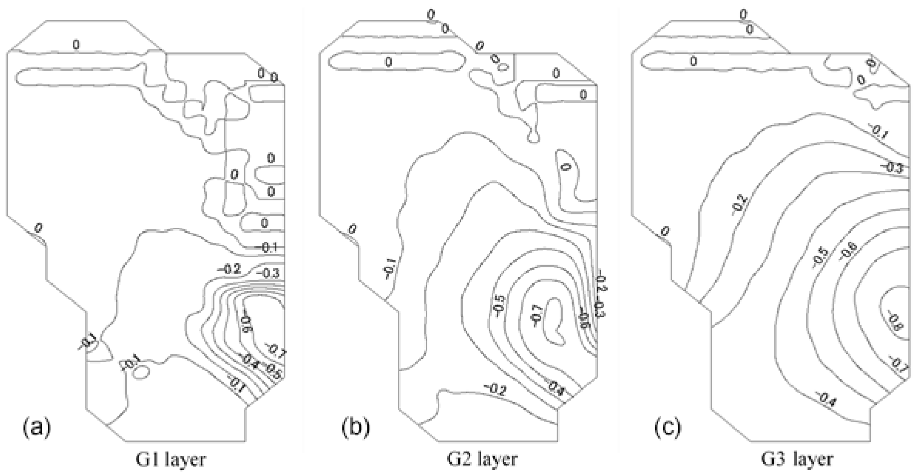

Figure 3. Groundwater level differences following well operation (Case 2) (m).

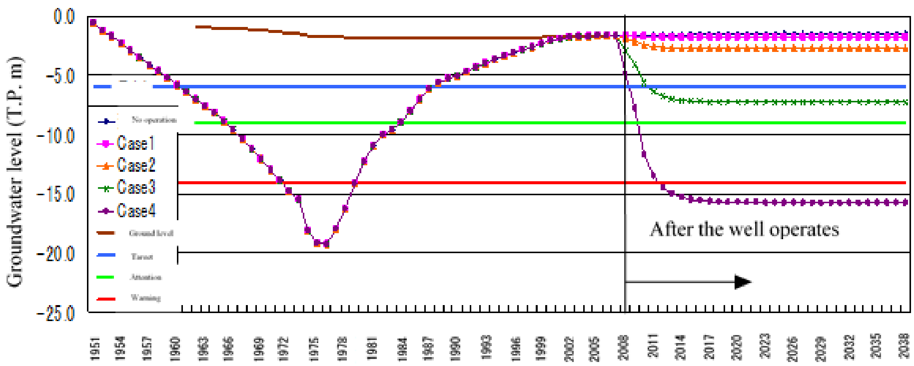

Figure 4. The yearly change of the groundwater level of Jushiyama observation well (G2 layer). "T.P." refers to Tokyo Peil.

4 Analytical results and consideration

It is common for the G1, G2 and G3 layers, as shown in Fig. 3, that when groundwater levels during the period of well operation are compared, a radial decrease in the groundwater level centering on the vicinity of the city of Nagoya can be observed. Next, the yearly change of the groundwater level in the vicinity of Jushiyama observation well is shown in Fig. 4. The secular distortion in the amount of subsidence accumulated is shown in Fig. 5. Groundwater can be pumped without lowering groundwater level and without land subsidence in Case 1 and Case 2 even if 30 years have passed since the wells operated. In Case 3, the groundwater level fell below the management target for a safe groundwater level in the prefecture of Aichi, and it was forecast that the accumulated subsidence of 30 years was 6.8 cm after the new wells had operated.

However, the subsidence gradually tends to stop as the amount of the subsidence during a year is less than 1 cm. It is thought that groundwater can be pumped, although there are some anxieties with regard to subsidence. In Case 4, when the lowering in the groundwater level after the well had been operating was remarkable and 30 years had passed since the well had operated, a remarkable accumulated subsidence of about 33.8 cm was forecast. Therefore, such groundwater withdrawal could not be done.

5 Conclusions

Here, the state of groundwater and ground-level changes in the future were predicted using a three-dimensional groundwater-flow analysis and a perpendicular one-dimensional consolidation subsidence analysis in order to examine how a large area of groundwater should be managed. As a result, for the amount of the groundwater pumping of Case 1 and Case 2, it has been understood that it would be possible to pump groundwater without causing a remarkable subsidence. Moreover, if the amount of the groundwater pumping that exceeds Case 3, it has been understood that the possibility of remarkable subsidence occurs. Therefore, $100\,\mathrm{L\,d^{-1}}$ per person in Case 3 was assumed to be a critical yield of groundwater. It was judged that groundwater could be continuously pumped if it was fewer than this critical yield.

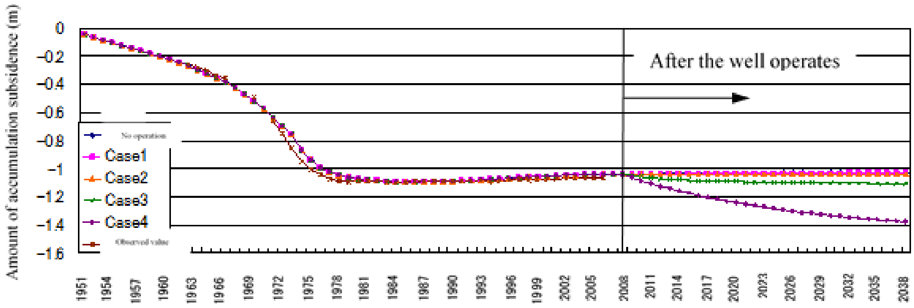

Figure 5. The yearly change of amount of accumulation subsidence in the vicinity of Jushiyama observation well.

Remarkable subsidence has occurred in the Nobi Plain in the past; therefore many of the clay layers are in a state of overconsolidation. This means that excessive subsidence may not occur even if a limited amount of groundwater were now to be pumped up. Moreover, the groundwater level forecast from the management target of a safe groundwater level is considerably higher in Case 1 and Case 2 in the G2 layer. Therefore, it is thought that steadier groundwater can be pumped by decreasing the pump discharge in the G1 layer and the G3 layer and increasing the pump discharge from the G2 layer.

Because pump discharge increases in proportion to the number of refuges and the size of the population, there is a comparatively remarkable drawdown in the groundwater level in a number of refugees in the vicinity of the populous city of Nagoya. The pump discharge in the vicinity of the city of Nagoya can be decreased along with an increase in the pump discharge in the vicinity of the city of Ogaki, with little reduction in the groundwater level. It is thought that this will mean that the possibility of subsidence decreases and can be used as a way to manage a large area of groundwater by transporting the shortfall to the vicinity of the city of Nagoya in the event of a disaster. Moreover, if groundwater of $100\,\mathrm{L\,d^{-1}}$ per person can be pumped, groundwater can be used as a water resource for improving water quality of the river and as a water for daily life after disaster. At this time, major subsidence has not occurred in the Nobi Plain.

Data availability. Data have been provided by Ministry of Health, Labour and Welfare (2007) and by Geospatial Information Authority of Japan, Ministry of Land, Infrastructure, Transport and Tourism (2019).

Competing interests. The author declares that there is no conflict of interest.

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