Recent countermeasures for land subsidence and groundwater resources in Japan

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Abstract The history of land subsidence in Japan can be traced back to the late 1930s. During the past century the suppression of the land subsidence has been a constant challenge in groundwater resources management. This paper deals with the latest measures for land subsidence. The current approach is rooted in optimizing the groundwater pumpage without land subsidence. Today, an adjusted approach is required for more groundwater to meet water shortages in the summer season.

INTRODUCTION

A history of land subsidence due to groundwater pumping in Japan can be traced back to the late 1930s. During World War II no land subsidence was observed because there was no increase in groundwater use and industry was suspended. Levelling results of land in several places in Osaka and Tokyo showed the response of land subsidence to the industrial and economical growth after the end of World War II. The demand for groundwater by industry since 1950 has increased tremendously and has brought serious land subsidence to several industrial areas. The use of water in 1993 in Japan is given in Table 1.

The lowland below sea level was a problem because of sea-water flooding caused by tidal storms and big typhoons. This became a serious social problem. The state and local governments started to request counter measure for land subsidence. The state law on industrial water has been enacted to control groundwater pumping in parts of some land subsidence areas since 1956. There have been no signs of a reduction in land subsidence, irrespective of whether the state law and regulation by local governments were enacted. Thus, the state law on industrial water has been revised to strengthen the control of groundwater withdrawals, and also the state government issued a law on groundwater pumping for building’s cooling water, which was in force in 1962 (Environment Agency of Japan, 1990). Figure 1 shows the history of land subsidence and groundwater use.

Countermeasures for land subsidence were improved by the development of new water resources in place of groundwater resources as well as industrial water supply projects. Land subsidence has expanded to industrialized and newly-developed cities. The pollution of groundwater with salt-water intrusion in coastal aquifers increased because of so much groundwater extraction. After the 1970s a numerical groundwater simulation technique was used to predict and to plan countermeasures for land subsidence. It was the time when computers started to become popular. In those days, studies of the prediction of land subsidence and allowable pumping volume by means of
Table 1 Water resources and water use in 1993 in Japan (after Environment Agency of Japan, 1994).

<table>
<thead>
<tr>
<th>Kind of use</th>
<th>Total volume:</th>
<th>Surface water and others:</th>
<th>Groundwater:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^9 \text{ m}^3 \text{ year}^{-1})</td>
<td>(10^9 \text{ m}^3 \text{ year}^{-1})</td>
<td>(10^9 \text{ m}^3 \text{ year}^{-1})</td>
</tr>
<tr>
<td>Industrial</td>
<td>10.70</td>
<td>12.3</td>
<td>7.65</td>
</tr>
<tr>
<td>Service water</td>
<td>16.74</td>
<td>19.2</td>
<td>13.10</td>
</tr>
<tr>
<td>Agricultural</td>
<td>58.60</td>
<td>67.3</td>
<td>54.72</td>
</tr>
<tr>
<td>Others</td>
<td>1.02</td>
<td>1.2</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Numerical groundwater simulation were reported from the cities of Tokyo and Osaka. In addition, the installation of new observation wells for measuring groundwater heads and land subsidence was required as groundwater simulation techniques became more advanced. Many of observation wells have been at depths of 100 ~ 300 m excepting those for deep geological boring wells.

The concept on optimal groundwater utilization and pumping for promoting the conservation of the groundwater as well as a countermeasure for land subsidence was investigated at the end of the 1980s. The state government tried to make a law on the conservation of groundwater, but it failed to pass the draft law because the common interests were not amended. A cabinet ministers’ meeting on countermeasures for land subsidence (nine ministers were present at the meeting) was held in November 1981. The meeting confirmed the guidelines for countermeasures for land subsidence at three basins: Nobi and Chikugo-Saga (1985) and Northern Kanto (1991). The effectiveness of the measures can be illustrated by the changes of land subsidence in space and time presented in Fig. 2.

The priority policy in Northern Kanto basin is to develop new water resources in place of excessive groundwater use under optimal groundwater pumping. The rules for groundwater pumping are based upon:
- optimization of the allocation and distribution of regional pumping volume,
- optimization of well locations and depths,
- optimal operation of pumping wells.

In planning the optimization policy, numerical simulation coupled with linear programming theory has been applied (National Land Agency of Japan, 1993).

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Fig. 1 A short history of land subsidence and groundwater use.
Countermeasures for land subsidence in Japan

In the last decade Japan has experienced serious water shortages every three or four years. How to use groundwater resources in the drought season is one of the important considerations.

COUNTERMEASURES FOR LAND SUBSIDENCE IN NORTHERN KANTO BASIN

Hydrogeology and background of land subsidence

The location of the Northern Kanto basin is shown in Fig. 3(a). The basin covers five prefectures (Saitama, Gunma, Ibaraki, Tochigi and Chiba), and the population in it is about ten millions. Three big rivers (Tone-gawa, Ara-kawa and Edo-gawa) flow through the basin. The average rainfall is 1284 mm year$^{-1}$ (Kumagaya, Saitama), and the annual temperature is 13.9°C.

Fig. 2 Change of land subsidence in Japan: (a) land subsidence areas, (b) trends of a typical land subsidence area (after Environment Agency of Japan, 1994).

Fig. 3 Location of Northern Kanto basin and its land subsidence.
The basin consists of several terraces and hills, and an alluvial plain 30 ~ 60 m a.m.s.l. The geology of the basin is classified into alluvial and diluvial deposits, Tertiary deposits and a bottom set bed of the Miocene. The depth of the hydrogeological base may be in the range of 1500 ~ 2000 m below m.s.l. The basin is located at the centre of the Kanto basin. The alluvial deposits are mainly composed of soft clay and sand. The land subsidence caused by the groundwater withdrawal is mainly due to soft clay. The diluvial deposits consist of sand, gravel and consolidated clay. The strata of the basin are complex. Groundwater is extracted mainly from depths between 100 and 300 m. The largest land subsidence has occurred since 1980. The total pumping discharge of groundwater was 660 million m$^3$ year$^{-1}$ in 1986. Figure 3(b) shows the Northern Kanto basin and land subsidence in 1991. The largest land subsidence contour is —40 mm in the northwest part of Saitama prefecture. The National Land Agency of Japan has determined a pumping goal of 480 million m$^3$ year$^{-1}$ using the following process.

**Determination of the goal for pumping discharge**

One of the most important tasks for the state guidelines for the basin is to determine a goal for pumping discharge without the occurrence of land subsidence (Sato et al., 1986; Specialist Committee on Preventive Measures for Land Subsidence, 1990). Two methods were adopted:
- empirical method based on relationship between land subsidence and pumping discharge;
- coupling numerical simulation with linear programming.

**Empirical method based on relationship between land subsidence and pumping volume** A pumping volume goal in a hydrogeological basin is defined as the sum of maximum (or allowable and optimal) pumping volumes without the occurrence of land subsidence in all sub-basins. The pumping volume goal must be less than the total recharge by precipitation.

The pumping volume can be determined from a set of relationships between land subsidence and pumping volume as follows. The average land subsidence $s_i$ in sub-basin $i$ ($i = 1, 2, 3, \ldots, N$) from a total pumping volume per year $q_i$ (Fig. 4) is calculated as:

$$s_i = \frac{1}{M} \sum_{j=1}^{M} s_{ij} \ldots$$  

(1)

in which $j$ is the number of benchmarks for land levels ($j = 1, 2, 3, \ldots, M$) at the $i$th sub-basin.

The total pumping discharge $q_i$ from the $i$th sub-basin and the total pumping discharge $Q$ from the basin are determined as follows:

$$q_i = \sum_{k=1}^{L} q_k \ldots$$  

(2)

$$q = \sum_{i=1}^{N} q_i \ldots$$  

(3)
where $L$ is the number of pumping wells in the $i$th sub-basin and $N$ is the number of sub-basins.

In practice the total pumping discharge per unit area ($\text{m}^3 \text{ } \text{year}^{-1} \text{ } \text{km}^{-2}$) is sometimes used. Based on several existing relationships between the total pumping discharge per unit area $q_i$ and averaged land subsidence $s_i$ in the $i$th sub-basin, a critical total pumping discharge $q_{ci}$ corresponding to $s_i = 0$ will be found practical as shown in Fig. 5. The goal for pumping discharge $Q_0$ in the whole basin will be estimated by:

$$Q_0 = \sum_{i=1}^{N} A_i \bar{q}_{ci} \cdots \tag{4}$$

in which $A_i$ is the area of the $i$th sub-basin.

This method is applicable for estimating the maximum pumping discharge in a hydrological basin equipped with many benchmarks for land levels over a decade or more.

**Method based on numerical simulation coupled with linear programming** Let us consider an optimizing problem of groundwater pumping discharge in a hydrological basin. The basin consists of $N$ sub-basins which usually are administrative districts as cities, towns or villages as shown in Fig. 6. The critical head at some sub-basins is specified and it is required to maximize the total sum of pumping discharges from the whole basin:

$$Q_0 = \sum_{i=1}^{N} q_{oi} \rightarrow \max \cdots \tag{5}$$

$$h_i \geq h_{ci} \cdots \tag{6}$$

$$\bar{s}_i \cdots$$

**Fig. 4** Pumping discharge $q_i$ and land subsidence $\bar{s}_i$ in sub-basins.

**Fig. 5** Relationship between $\bar{q}_i$ and $\bar{s}_i$. 
The basic equation of groundwater flow is where \( x, y \) are horizontal coordinates, \( T \) is transmissivity, \( h \) is groundwater head, \( K \) is permeability of the confining layer, \( b \) is thickness of the confining layer, \( H \) is groundwater head in unconfined aquifer, \( R \) is natural recharge rate, \( q \) is pumping discharge rate, \( N_q \) is number of pumping wells, \( d \) is Dirac delta, \( S \) is storativity, \( t \) is time and \( k \) is the number of the aquifer.

Applying FEM to equation (7) at the steady state results in a set of linear simultaneous equations expressing the relation between head \( h \) and pumping discharge \( q \). Linear programming will give the optimal pumping discharge \( q_{oi} \) at each sub-basin \( i \) and the total pumping discharge goal \( Q_0 \). The most important aspect in this method is the determination of the critical head \( h_{ci} \) because it often involves some legal and administrative matters as well as scientific reality. A typical application of this method is shown in Fig. 6. The overall methodology of the computation of the optimal pumping discharge and its distribution in terms of required groundwater use plan under restricted conditions is shown in Fig. 7.

**OBSERVATION SYSTEMS OF GROUNDWATER AND LAND SUBSIDENCE**

There are many groundwater observation wells all over Japan. They can be classified into three kinds: shallow wells for measuring shallow groundwater, deep wells which consist of double pipes and single pipe wells, which have been adopted from abandoned pumping wells. Usually, observation wells are less than 700 m deep, except those for seismic measurements, and most deep wells are 100 ~ 300 m. Geological, mechanical and hydraulic surveys are carried out by boring. Several wells with different depths are bored in the same place; the groundwater heads of different aquifers can then be
measured, as well as the land subsidence at each depth. There is also a number of shallow observation wells used to measure shallow groundwater behaviour up to depths of several tens of metres. The data give us precise information to estimate the natural recharge and infiltration by precipitation. Figure 8 shows a typical observation well and

Fig. 7 Numerical computation procedure for groundwater use plans.

Fig. 8 A typical observation well and its recording devices.
its recording equipment. Monitoring and maintenance of wells are performed by several state ministries and agencies, and by many prefectural governments (Sato, 1988).

Recently, as the number of observation wells has increased in large basins and modern technology has advanced, automated observation systems are being introduced. Several new types of data processing equipment have been developed along a conceptual process (Fig. 9).

Real-time data collection and processing are useful for the achievement of safe groundwater utilization, preventing land subsidence.

Highly accurate level measurements are carried out in many basins once a year (in winter, when the land subsidence abates) to measure land subsidence. The results of these measurements are shown as contour lines on topographical maps. In addition, pumping volume and atmospheric data are collected in every city and basin. The simultaneous measurement of groundwater heads at a number of pumping wells can be performed whenever the occasion demands.

![Data processing concept](image)

**CONCLUSION**

In Japan there has been a long tradition of countermeasures for land subsidence for at least half a century. The history and current state are summarized as follows:

- The historical stages with respect to countermeasures for land subsidence were; a significant increase of land subsidence in big cities during about 10 years after World War II; regulation of industrial groundwater use by state and local government laws since 1956; and a localizing and land subsidence extending to local cities in the vicinity of big cities in later years.
- The state government (National Land Agency) issued guidelines in three different areas (Saga-Chikugo plain in Kyushu, Nobi plain and Northern Kanto plain on the main land) to arrest serious land subsidence.
- Most countermeasures for land subsidence have been planned through computers using numerical simulation techniques coupled with optimization theories. The use of computers been popular since the mid 1970s.
- The current concept of countermeasure for land subsidence is concentrated on optimal groundwater pumpage in the following ways: (i) optimization of local allocations or distribution in groundwater pumping volume, (ii) optimization of pumping wells in depth and location, and (iii) optimal operation of pumping wells in avoiding a rapid groundwater drop.

Finally, two future problems are foreseen. Most data collecting systems in Japan use traditional charts at observation sites. There is a need for a more systematic observation
of groundwater and land subsidence measurements. Another is land subsidence resulting from abnormal groundwater withdrawal in drought seasons. Some serious droughts have been experienced every three or four years in summer. The occurrence of abnormal land subsidence has been a matter of concern.

REFERENCES


