Monitoring groundwater temperature change due to pumping

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Abstract From the long-term monitoring of groundwater temperature in Nara basin, Japan, the temperature in the discharge area of the basin decreased by a few degrees centigrade during the last three decades, although each element of water balance in the basin has not been changed, except groundwater pumpage in the discharge area. A thermal transport model that incorporates the effect of pumping has been developed to simulate the decrease in groundwater temperature. The calculated groundwater temperatures in the discharge area agree well with the temperatures monitored during the last three decades. The model is useful for evaluating the long-term change in groundwater temperature due to pumping.

INTRODUCTION

As heat in aquifers is transported by advection as well as conduction, it is possible to determine the change in the groundwater flow regime by monitoring groundwater temperature and to estimate groundwater flux by using temperature as a tracer. Studies of the estimation of one-dimensional groundwater flux using steady-state temperature profiles (Bredehoeft & Papadopulos, 1965; Boyle & Saleem, 1979), transient temperature responses (Stallman, 1965; Lapham, 1989; Taniguchi, 1993; Shimada et al., 1993), and studies of two-dimensional groundwater flow (Domenico & Palciauskas, 1973; Taniguchi et al., 1989; Sakura, 1993) have been made.

However, in those studies the groundwater temperatures were monitored for relatively short periods of time and the studies were limited to the estimation of the groundwater flux. Studies on long-term change in the thermal regime for assessing the change in the groundwater flow regime and studies on the effect of pumping on the thermal regime are quite few. The objectives of this study are to develop a thermal transport model that incorporates the effect of changes in hydraulic head due to pumping of groundwater, and to simulate the changes in groundwater temperature monitored over the long term.

STUDY AREA

Figure 1 shows the location of the study area, Nara basin (772 km²), Japan. Nara basin consists of a sand and gravel alluvial plain surrounded by terraces of Pleistocene age to
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the east and by hills of late Pliocene to early Pleistocene age to the north and northeast. Many tributaries in the Nara basin meet to form the Yamato River near the center of the basin (Fig. 1).

The groundwater table elevations measured in October, 1991 are shown in Fig. 1. According to a flownet analysis along the Yamato River, the transmissivity of the aquifer was calculated to be about $1.43 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$. The annual groundwater recharge rate is estimated to be 459 mm year$^{-1}$ by using a type-curve analysis (Taniguchi, 1993) of transient groundwater temperature data (Taniguchi, 1994). From the groundwater flow line (a-b) in Fig. 1, the distance from the end of the recharge area to the end of the
discharge area in the basin is estimated to be 21 km. According to the borehole data, the depth of the aquifer is estimated to be 225 m. The difference in water levels between the endpoints of the recharge and the discharge area is about 90 m.

MONITORING GROUNDWATER TEMPERATURE CHANGE

Groundwater temperatures in the discharge area of the basin were monitored from November 1970 to July 1993 in 17 wells shown as solid circles in Fig. 1. Groundwater temperatures throughout the basin were also measured in 43 wells shown as open and solid circles in Fig. 1 on 5-20 July, 1993. Most wells used in this study have depths from 75 m to 185 m below the surface. The mean of the central depth of screens is 125 m and the mean length of the screens is 110 m. Groundwater temperatures were measured using thermometers when the temperature became stable after sufficient pumping.

Figures 2(a) and 2(b) show examples of temporal changes in groundwater temperature observed at well no. 1 and no. 2 (see Fig. 1), with approximated straight lines. The center depths of the screen of well no. 1 and no. 2 are 123 m and 114 m below the surface, respectively. From the regression lines determined by the least-squares method, the decreases in groundwater temperature during the last three decades were 2.35°C and 2.08°C at well no. 1 and no. 2, respectively. The temperature at the other wells mostly decreased by 1-2°C depending on the depth of the well screens.

Fig. 2 Temporal changes in the groundwater temperature at (a) well 1 and (b) well 2.
Therefore, the groundwater temperature in the discharge area of the basin decreased by a few degrees centigrade during the last three decades.

According to meteorological and geophysical data in this study area, there is no significant change in precipitation, evapotranspiration, air temperature and terrestrial heat flow in the basin during the last three decades. Nevertheless, the groundwater temperature in the discharge area decreased by a few degrees centigrade during that time.

CHANGES IN HYDRAULIC HEAD DUE TO PUMPING

The only remaining element of the water balance in the basin, groundwater pumpage, has changed during the last three decades. Figure 3 shows the temporal change of the pumpage at 17 wells shown as solid circles in Fig. 1 which are located in the discharge area of the basin. Figures 4(a)-(d) show the temporal changes in hydraulic head at wells no. 1, no. 3, no. 4 and no. 5, which are located in the discharge area of the basin (Fig. 1). The center depths of the screen of the wells range from 117 m to 125 m below the surface.

Because the groundwater pumping at wells shown as solid circles in Fig. 1 was initiated in 1968, the hydraulic heads in those wells in 1963 are assumed to be the same as those in 1968. During the last three decades, the hydraulic heads of the groundwater at a depth of about 120 m below the surface decreased by about 35 m. These decreases in the discharge area of the basin are caused by the pumping of the groundwater from the basin.

MODEL DESCRIPTION

In order to simulate the change in groundwater temperature monitored during the last three decades, a heat transport model that incorporates the effect of groundwater pumping has been developed.

According to the observed groundwater table (Fig. 1), we may assume a vertical two-dimensional (line a-b in Fig. 1) thermal and groundwater flow regime with an
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![Graphs showing temporal changes in hydraulic head at different wells](image)

Fig. 4 Temporal changes in the hydraulic head (meter above sea level) at (a) well 1, (b) well 3, (c) well 4, and (d) well 5.

Assumption of groundwater potential \( h(x) \) at \( z = z_0 \) (upper boundary) in the form, \( h(x) = A - B \cos(\pi x/L) \), where \( x \) is the horizontal coordinate, \( A \) and \( B \) are constants, and \( L \) is the distance from the end of the recharge to the discharge area in the basin. The potential distributions are described as

\[
h(x, z) = A - \left[ B \cosh(\pi z/L) / \cosh(\pi z_0/L) \right] \cos(\pi x/L)
\]

A first-order approximation of heat conduction-convection for the flow solution described by equation (1) was solved by Domenico & Palciauskas (1973) and becomes

\[
T(x, z) = T_1 + T'_0 (z - z_0) - \left( T'_0 K B / 2 \alpha \right) \left[ \cosh(\pi z/L) / \cosh(\pi z_0/L) \right] \\
\times \left\{ \left( z_0 - z \right) \cosh(\pi z/L) + (L/\pi) \left[ \sinh(\pi (z - z_0)/L) / \cosh(\pi z_0/L) \right] \right\}
\]

where \( T_1 \) is the constant temperature at the upper boundary, \( T'_0 \) is the constant temperature gradient across the lower boundary, \( \alpha \) is the thermal diffusivity and \( K \) is the hydraulic conductivity.

To evaluate the change in hydraulic head due to pumping, one may assume that the decrease of the hydraulic head due to pumping from \( h'(x,z) = h(x,z) + \Delta h(x,z) \) at the past time to \( h(x,z) \) at the present is equivalent to the change of \( B \) in equation (1) from \( B' \) to \( B \). Therefore, the relationship between \( B' \) and \( B \) can be obtained from equation (1), with assumptions of the same \( z_0 \) and \( A \), to be

\[
B' = B + \Delta h(x, z) / \left\{ 1 - \cos(\pi x/L) \left[ \cosh(\pi z/L) / \cosh(\pi z_0/L) \right] \right\}
\]

MODEL PARAMETERIZATION

Groundwater temperatures observed in 1993 are used for the model parameterization.
The values of \( z_0 = 225 \text{ m}, L = 21 \text{ km} \) and \( B = 45 \text{ m} \) are substituted into equation (2). The upper boundary of the temperature, \( T_1 \), and the lower boundary of the thermal gradient, \( T_0' \), were estimated to be 14.0°C and 0.05°C m\(^{-1}\), respectively. After developing the two-dimensional thermal transport model in the basin by using equation (2) and parameters mentioned above, the relationship between groundwater temperature \( (T) \) measured at 43 wells in 1993 and the distance \( (x) \), \( T = -0.298x + 23.4 \), was compared to the calculated temperature-distance relationship to obtain the best fitted value of \( KB/\alpha \). The average calculated temperature from 75 m to 185 m depth below the surface were used for the representative groundwater temperature at each distance because most wells have screens from 75 m to 185 m below the surface. The best fitted value of the dimensionless parameter, \( KB/\alpha \), was 1227 for the groundwater flow regime in 1993.

**SIMULATING GROUNDWATER TEMPERATURE**

To evaluate the effect of the decrease in hydraulic head due to pumping, an analysis of \( B' \) using equation (3) has been made. Table 1 shows the results of the decreases in hydraulic head obtained from Fig. 4 and \( B' \) calculated from equation (3), at \( z = 120 \text{ m} \) in the discharge area \((x=L/4)\), from 1963 to 1993. Therefore, one can calculate the groundwater temperature by using the thermal transport model that incorporates the effect of pumping by substituting \( B' \) instead of \( B \) into equation (2). Substituting \( x=L/4 \) in the discharge area, \( z=120 \text{ m} \) and the data in Table 1 into equation (2), we can calculate the temporal change in groundwater temperature in the discharge area during the last three decades.

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<td>( B' ) (m)</td>
<td>2.68B</td>
<td>2.68B</td>
<td>1.96B</td>
<td>1.48B</td>
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Figure 5 shows the temporal change in the groundwater temperature at the depth of 120 m below the surface in the discharge area \((x=L/4)\) of the basin. The decrease in groundwater temperature calculated by using the model was 2.73°C during the last three decades. The calculated groundwater temperatures (Fig. 5) agree well with the observed temperatures (Fig. 2). Therefore, the thermal transport model that incorporates the effect of a decrease in hydraulic head due to pumping can explain the decrease in groundwater temperatures in the discharge area of the basin.

**CONCLUSIONS**

The groundwater temperature in the discharge area of Nara basin decreased by a few degrees centigrade during the last three decades, as a result of an increase in groundwater flux caused by a pumping-induced decrease in hydraulic head in the
discharge. A thermal transport model that incorporates the effect of pumping has been developed to simulate the temporal change in groundwater temperature. Calculated temperatures agree well with the monitored temperatures; therefore, the model developed in this study is useful for monitoring the long-term change in the groundwater flow regime caused by pumping.

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**REFERENCES**


