



Temperature change affected groundwater quality in a confined marine aquifer during long-term heating and cooling



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ABSTRACT

Global warming and urbanization together with development of subsurface infrastructures (e.g. subways, shopping complexes, sewage systems, and Ground Source Heat Pump (GSHP) systems) will likely cause a rapid increase in the temperature of relatively shallow groundwater reservoirs (subsurface thermal pollution). However, potential effects of a subsurface temperature change on groundwater quality due to changed physical, chemical, and microbial processes have received little attention. We therefore investigated changes in 34 groundwater quality parameters during a 13-month enhanced-heating period, followed by 14 months of natural or enhanced cooling in a confined marine aquifer at around 17 m depth on the Saitama University campus, Japan. A full-scale GSHP test facility consisting of a 50 m deep U-tube for circulating the heat-carrying fluid and four monitoring wells at 1, 2, 5, and 10 m from the U-tube were installed, and groundwater quality was monitored every 1–2 weeks. Rapid changes in the groundwater level in the area, especially during the summer, prevented accurate analyses of temperature effects using a single-well time series. Instead, Dual-Well Analysis (DWA) was applied, comparing variations in subsurface temperature and groundwater chemical concentrations between the thermally-disturbed well and a non-affected reference well. Using the 1 m distant well (temperature increase up to 7 °C) and the 10 m distant well (non-temperature-affected), the DWA showed an approximately linear relationships for eight components (B, Si, Li, dissolved organic carbon (DOC), Mg²⁺, NH₄⁺, Na⁺, and K⁺) during the combined 27 months of heating and cooling, suggesting changes in concentration between 4% and 31% for a temperature change of 7 °C.

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1. Introduction

An increase in subsurface temperature (subsurface thermal pollution) has been recognized below several large cities worldwide (Harris and Chapman, 1997; Pollack et al., 1998; Huang et al., 2000; Taniguchi et al., 2003; Perrier et al., 2005; Taniguchi et al., 2007; Kooi, 2008). For example, a study in the Netherlands showed an approximately 0.8 °C increase at 20 m depth over the last three decades (Kooi, 2008). The temperature changes are strongly associated with surface warming effects such as global warming and urbanization (Huang et al., 2000; Taniguchi et al., 2003). Thus, a rapid increase in temperature in the subsurface

can be expected due to the combined effects of surface warming and subsurface infrastructures (including subways, shopping complexes, sewage systems, and Ground Source Heat Pump (GSHP) systems). Among these subsurface infrastructures, GSHP systems have gained popularity recently in many parts of the world as a highly promising renewable energy technology for cooling and heating buildings (Sanner et al., 2003; Spitler, 2005; Banks, 2008; Yang et al., 2010; Dinçer and Rosen, 2011; Lund et al., 2011; Bayer et al., 2012). Subsurface temperatures may decrease during GSHP heating, while GSHP systems used for cooling discharge waste heat into the subsurface environment, which could induce a subsurface temperature increase in the vicinity of the system (Sowers et al., 2006; Rybach and Eugster, 2010; Haehnlein et al., 2010; Bonte et al., 2011; Hähnlein et al., 2013). The degree of subsurface temperature change and the area of impact will depend on numerous factors including the configuration and scale, operational

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conditions of the GSHP system, and hydrogeological conditions at the installation location.

Temperature changes could trigger changes in physical, chemical, and microbial processes in the subsurface environment, resulting in groundwater quality changes (Banks, 2008; Bonte et al., 2011; Hähnlein et al., 2013). Previous studies have mainly investigated the impacts of temperature increase on subsurface processes including water flow, mineral weathering, chemical adsorption and desorption, gas solubility, and microbial redox processes. Based on several laboratory experiments using aquifer materials, carbonate precipitation, silicate dissolution, and mobilization of cations (Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+}), heavy metals and trace elements (B, Si, P, V, Fe, As, and Mo), and dissolved organic carbon (DOC) as well as progression to strongly reductive conditions, such as sulfate reducing and methanogenic conditions, were observed (Brons et al., 1991; Griffioen and Appelo, 1993; Bonte et al., 2013a, 2013b, 2013c; Jesuřek et al., 2013).

However, the potentially negative impacts on the subsurface environment during artificially induced thermal pollution (heat discharge) or cooling and their temperature-dependent effects on groundwater quality during temperature fluctuations have not been sufficiently studied and clarified. In particular, there are virtually no studies representing field-scale conditions. Full-scale in-situ experiments during controlled temperature loading (heating and cooling) of the subsurface environment are therefore essential to investigate potentially harmful impacts of changes in groundwater quality during subsurface temperature changes and fluctuations.

The main objectives of this study were: (i) to mimic GSHP system operation and its effects in a shallow marine groundwater aquifer during full-scale, in-situ, and long-term heating and cooling experiments by establishing a closely controlled GSHP heating and cooling test site on the campus of Saitama University near the Tokyo metropolitan area of Japan, (ii) to monitor spatial and

temporal changes in the subsurface temperature and temporal changes in as many as 34 groundwater quality parameters during long-term thermal experiments, and (iii) to apply Dual-Well Analysis (DWA) to better quantify the effects of subsurface temperature changes on groundwater quality in a confined marine aquifer in order to evaluate the temperature dependence during subsequent heating and cooling periods.

2. Materials and methods

2.1. Site description

The experimental site was established at the Saitama University campus ($35^\circ 51' 44.146''$ N, $139^\circ 36' 34.034''$ E) in the Arakawa Lowland near the Tokyo metropolitan area of Japan (Fig. 1a). At this site, a full-scale GSHP test facility consisting of a 50 m deep heat exchanger (double U-tubes) was installed with silica sand (mined from the Kashima district, Ibaraki, Japan) as backfill material. Platinum resistance temperature detectors (R36, Nihondensoku Co., Ltd.) were placed at the inlet and outlet of the U-tube heat exchanger to measure the heat-carrying fluid temperature (Fig. 1b). Four groundwater monitoring wells were installed at 1 m (W1), 2 m (W2), 5 m (W5), and 10 m (W10) distance from the U-tube as the heat source. Strainer screens were situated at depths corresponding to the two confined groundwater aquifers at the study site, the upper marine aquifer (Holocene) (strainer depth: 15.51–18.36 m below the surface) and lower non-marine aquifer (Pleistocene) (strainer depth: 37.70–40.01 m). R36 platinum resistance temperature detectors were also placed at five depths (10, 20, 30, 40, and 50 m) near the U-tube heat exchanger and at 10 depths (approximately 5, 10, 17, 23, 27, 31, 36, 39.5, 44, and 49 m) outside the walls of all four monitoring wells to measure subsurface temperatures.

The hydrogeological conditions of the upper and lower aquifers are markedly different (Table 1 and Fig. 2). A previous study carried

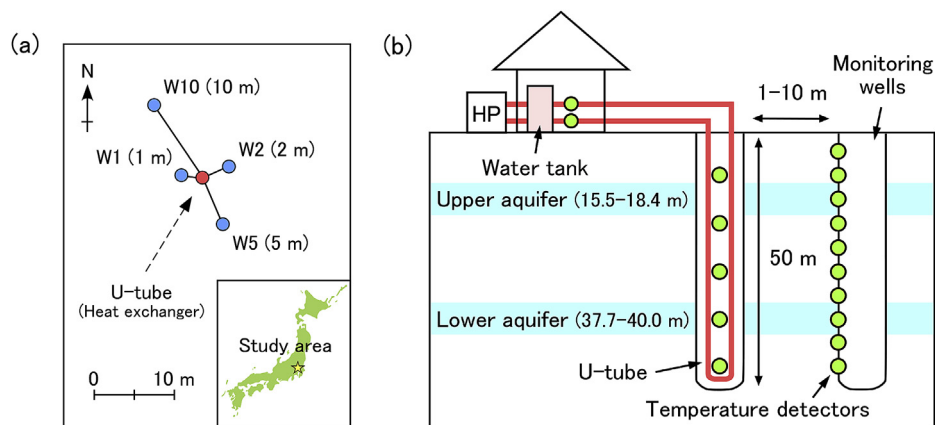


Fig. 1. (a) Location of the experimental site on the Saitama University campus in the Arakawa Lowland near the Tokyo metropolitan area of Japan, and (b) schematic of the in-situ experimental set-up for the long term enhanced heating and natural and enhanced cooling test.

Table 1

Hydrogeological properties of sediments from upper (marine) and lower (non-marine) groundwater aquifers: particle size (%), BET surface area (m^2/g), total carbon (%), electric conductivity: EC ($\mu\text{S}/\text{cm}$), pH, and saturated hydraulic conductivity (m/s).

Hydrogeological properties	Upper aquifer (marine)	Lower aquifer (non-marine)
Particle size (%)	Gravel (0), Sand (84.3), Silt (12.4), Clay (3.1)	Gravel (81.0), Sand (16.9), Silt (1.7), Clay (0.4)
BET surface area (m^2/g)	18.2	7.1
Total carbon (%)	0.6	0.4
EC ($\mu\text{S}/\text{cm}$)	283.7	43.7
pH	7.1	7.2
Saturated hydraulic conductivity (m/s)	3.0×10^{-7}	4.3×10^{-6}

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