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Evaluations of groundwater discharge rates from subsurface temperature in Cockburn Sound, Western Australia

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Abstract. Groundwater discharge rates were estimated from borehole groundwater temperature and pore water temperature under the seabed to be 0.92–3.6 cm/day in Cockburn Sound, Western Australia. Automated and manual seepage meters measured larger groundwater discharge rates of 13.7–16.3 cm/day. This difference may be because the observed seepage rates measured by seepage meters include not only terrestrial fresh groundwater discharge but also recirculated salt water. On the other hand, the discharge rates estimated from subsurface temperature may consist of only terrestrial fresh groundwater discharge.

Introduction

Temperature can be used as a tracer to evaluate groundwater fluxes because heat in subsurface environments is transported by conduction and advection caused by groundwater flow. Bredhoeft and Papadopulos (1965) developed type curves for estimating one-dimensional groundwater fluxes based on a steady heat conduction–advection equation. This type curve method was applied to estimate one-dimensional, vertical and horizontal groundwater fluxes (Stallman 1965; Boyle and Saleem 1979; Jessop and Vigrass 1989; Lu and Ge 1996). Simultaneous movement of one-dimensional transient heat and steady water flow has also been analyzed (Taniguchi 1993; Taniguchi et al., 1999a,b). Domenico and Palciauskas (1973) analyzed a two-dimensional subsurface thermal regime with regional groundwater flow. Their results, and the studies using type curves, show that groundwater temperature–depth profiles in aquifers with downward water fluxes are concave (which means the temperature gradient increases with depth), those with upward fluxes are convex, and those without vertical fluxes have constant gradient. Therefore, the vertical thermal gradient provides information about the vertical component of groundwater flux. More recently, surface warming caused by global warming and urbanization (Taniguchi et al. 1999a) and deforestation (Taniguchi et al. 1999b) was used as a signal to estimate groundwater fluxes. Taniguchi et al. (1999a,b) used borehole temperature data near the coast to estimate submarine groundwater discharge (SGD) into Tokyo Bay, Japan. Borehole temperature data was also used to evaluate a saltwater–freshwater interface in Toyama Bay, Japan (Taniguchi 2000). All of these studies suggest that temperature–depth profiles in the coastal zone can be used to evaluate groundwater discharge rates including SGD.

Accurate evaluation of SGD is important for coastal management and assessment of seawater contamination by groundwater. However, there are many uncertainties in quantifying SGD, and measurements of SGD on the seabed are hard to obtain. By comparison, groundwater temperature data at many depths in one borehole is relatively easy to obtain. The purposes of this study are to (1) evaluate the groundwater discharge rates in coastal regions using borehole temperature data and pore water temperature data from under the seabed, and (2) compare the groundwater discharge rates estimated from subsurface temperature to those measured by seepage meters.

Study area and data collection

The experimental site for the study (Figure 1) was located near to Northern Harbour, approximately 10 km south of Fremantle in Western Australia. Smith and Hick (2001) describe the hydrogeology and aquifer water balance for this region of the Swan Coastal Plain. Superficial sediments consisting predominantly of limestone overlain by sand extend to a depth of approximately 30 m below sea level. Beneath this is a relatively impermeable aquitard consisting of Cretaceous sandstone, siltstone and shale. Shallow groundwater is recharged by rainfall infiltration through well-drained sandy soils and un-utilized groundwater drains laterally toward the coast and discharges along the shoreline of Cockburn Sound. All bores considered in this study are installed into the shallow groundwater system within the superficial sediments.

Temperature measurements in boreholes were collected using a calibrated thermistor at 50 cm intervals from the water table to the bottom of the boreholes. Electrical conductivity (EC) was measured at the same intervals. These data were collected on two occasions, 29 February 2000 and 28–29 November 2000.

SGD at E1 (Figure 1, insert C) was measured using a Lee type manual seepage meter (Burnett and Turner 2001) as well as an automated seepage meter every 5 min during the period from 8:00 pm 28 November 2000 to 10:00 am 4 December 2000. The automated seepage meter used the principle of heat convection caused by water flow. The basis of the method is measurement of the temperature gradient between the downstream and upstream positions of the flow tube through which SGD is amplified. The meter is described in detail by Taniguchi and Iwakawa (2001), and compared with other types of seepage meter by Taniguchi et al. (this issue).

Submarine pore water temperatures at different depths were measured every 5 min near to the sea level gauge inside of Northern Harbour (Figure 1, insert C)

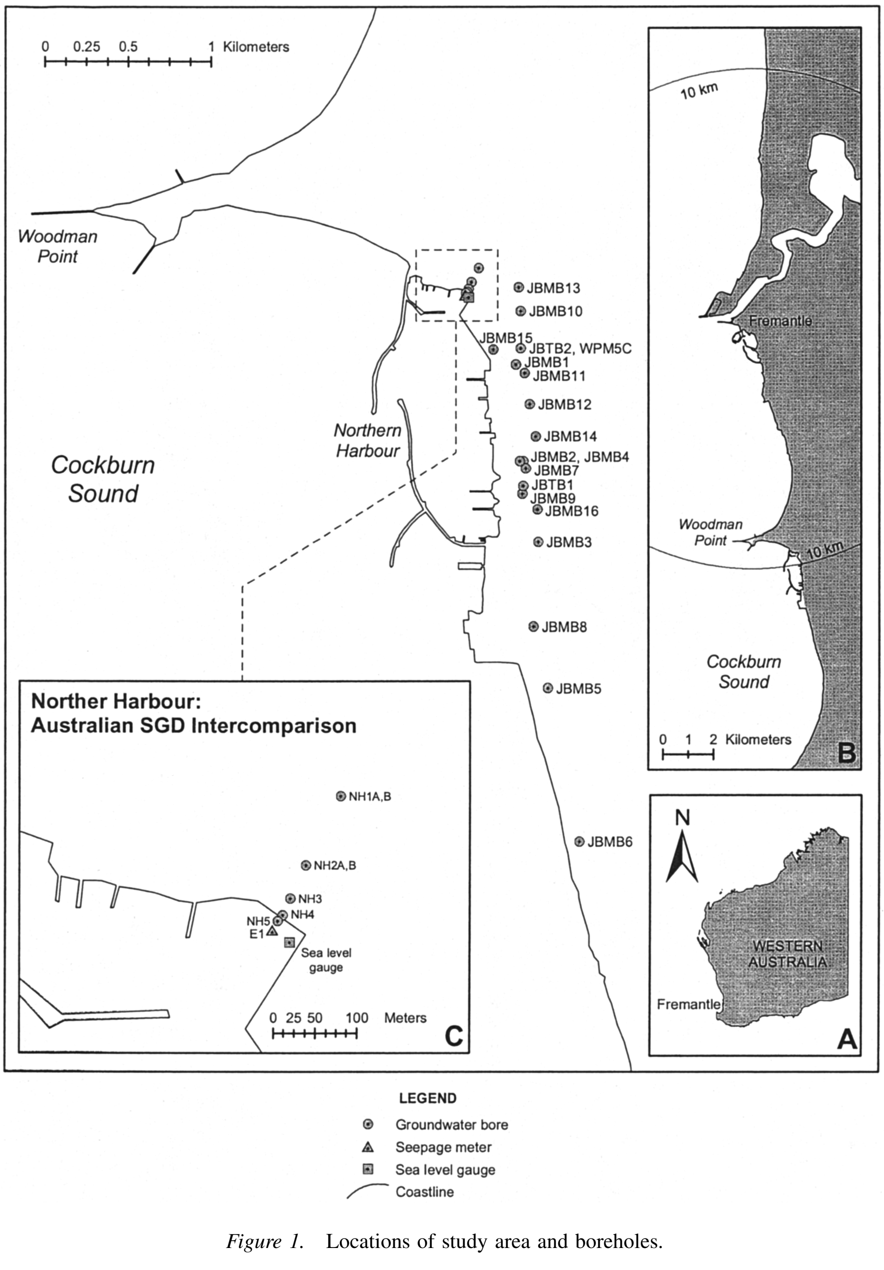

Figure 1. Locations of study area and boreholes.

using thermistor thermometers. The measurement depths were 5, 10, 30 and 50 cm below the seabed and data was collected during the period 1:00 pm 27 November 2000 to 7:00 pm 6 December 2000.

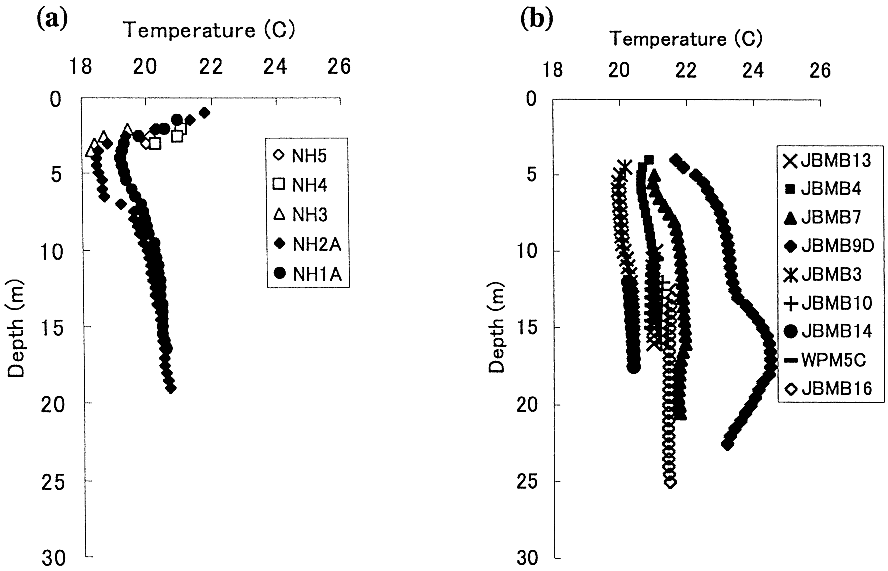

Figure 2. Temperature–depth profiles in boreholes for (a) NH1–NH5 (near the locations of seepage measurements), and (b) others, measured on 28 and 29 November 2000.

Temperature–depth and salinity–depth profiles in boreholes

Temperature–depth profiles measured in 14 boreholes on 28 and 29 November 2000 (early summer) are shown in Figures 2(a and b). To evaluate the seasonal change in subsurface temperature, temperature–depth profiles measured on 29 February 2000 (late summer) are shown in Figures 3(a and b). According to the vertical two-dimensional steady groundwater and heat flow analyses by Domenico and Palciauskas (1973), groundwater temperature in the discharge area is higher than at the same depth in the recharge area. Furthermore, groundwater temperature in the discharge area increases with increasing groundwater discharge rates, and temperature decreases in the recharge area with increasing recharge rates. As can be seen from Figures 2 and 3, groundwater temperature at JBMB9 (Figures 2(b) and 3(b)), JBMB7 (Figures 2(b) and 3(b)), JBTB1 (Figure 3(b)), and JBMB16 (Figure 2(b)) is higher than in other bores. One explanation is that high temperature may be caused by high groundwater discharge rate and convective heat flow. However, high subsurface temperatures in this area may be the result of high point source nitrogen inputs in this area inshore from the coast; the resulting nitrogen-rich groundwater plume probably discharges into Cockburn Sound and nitrogen concentrations are significantly elevated in JBMB7, JBMB9 and JBTB1. Elevated temperature in these wells indicate the possibility that the plume is biologically active and exothermic. Convex profiles of groundwater temperature between 5.5 and 15.5 m depth in NH1A and between 6.5 and 18.5 m in NH2A can be used to evaluate groundwater discharge rates.

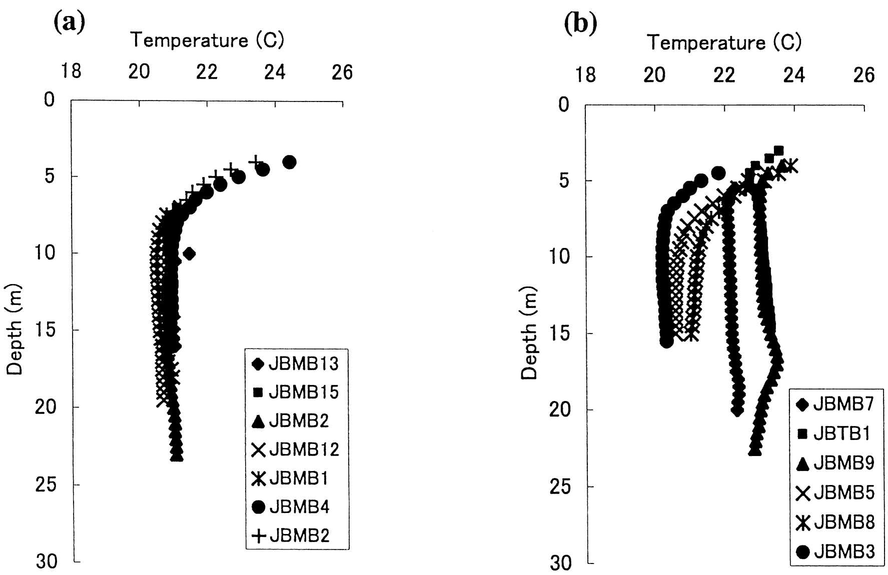

Figure 3. Temperature–depth profiles measured on 29 February 2000.

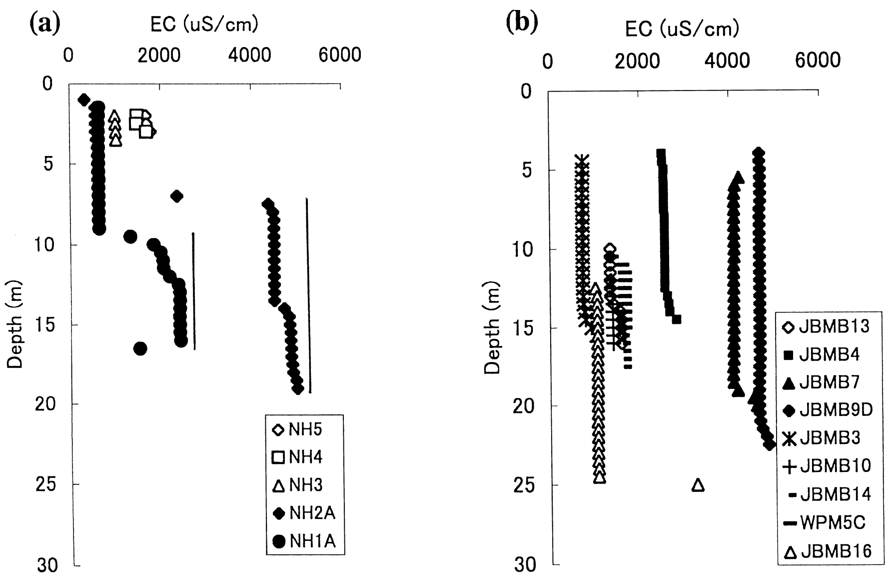

Figure 4. Electrical conductivity–depth profiles in boreholes for (a) NH1–NH5 (near the locations of seepage measurements), and (b) others, measured on 28 and 29 November 2000. The bars in (a) shows the depths of screen of NH1A and NH2A.

EC measured in 14 boreholes on 28 and 29 November 2000, are shown in Figures 4 (a and b). Significant and abrupt increases in groundwater conductivity occurred at depths of 7 and 9 m below the surface in NH2A and NH1A, respectively. Small increases in groundwater temperature were also measured at these depths (Figure 2(a)). To interpret the temperature data, it is reasonable to assume that there is thermal equilibrium between the inside and outside of a bore over both screened and unscreened sections; however, it cannot be assumed that the EC of water inside of an unscreened section of bore is representative of groundwater EC outside of the bore. Bores NH1A and NH2A are screened over the bottom 6-m of hole only and the abrupt increases in EC occur approximately at the elevations of the tops of the screens. Generally speaking, the EC of shallow groundwater was highest near to the coast at NH5, and decreased with increasing distance from the coast.

Continuous measurements of SGD and pore water temperature

Changes in SGD measured by the automated seepage meter at E1 are shown in Figure 5 as well as tidal elevation data observed by the sea level gauge (Figure 1(C)). The average of SGD rate during the observation period (from 8:00 pm 28 November 2000 to 10:00 am 4 December 2000) was 16.3 cm/day. This compares with SGD measurements made using manual Lee-type seepage meters (Lee 1977), which at E1 had daily-average values of 3.8, 7.9, 14.2, 13.3, 24.2 and 18.8 cm/day for 28, 29, 30 November and 1, 2,3 December, respectively (Burnett and Turner 2001). The general increase of SGD may be caused by the general decrease in tidal elevation. The average SGD measured using the manual seepage meter at E1 was 13.7 cm/day. Figure 5 indicates that diurnal variations of SGD were observed. Taniguchi et al. (this issue) observed semi-diurnal variations of SGD in the Gulf of Mexico, and Taniguchi (2002) measured both diurnal and semi-diurnal variations of SGD due to tidal effects in Osaka bay, Japan.

Change in pore water temperature at depths of 5, 10, 30 and 50 cm below the seabed is shown in Figure 6. Diurnal variations in pore water temperature were observed and may have been caused by diurnal variation in air temperature. The depth of seawater near the sea level gauge was less than 1 m during the observation period; diurnal variation of air temperature may have penetrated to the measurement depths with time lags.

Krupa (2002) measured seawater temperatures in the range of 21.5–23.8 °C during the same period that pore water temperatures were collected. Therefore, shallow pore water temperatures less than 21 °C may indicate groundwater discharge. Also, although the tide and solar heating were both diurnal, they had different phases during the observation period. High tide occurred around midnight and low tide around 9 am–12 pm in the morning. This could account for the bimodal temperature response in pore water temperature at the depths of 5 and 10 cm below the seabed, as indicated in Figure 6.

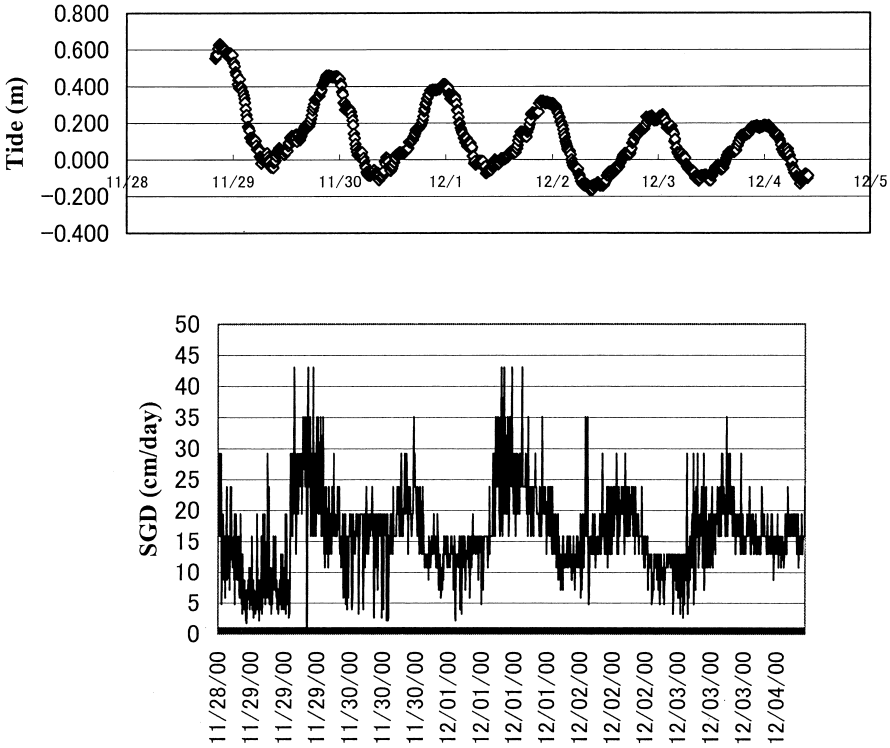

Figure 5. Changes in tide and SGD at E1 from 8:00 pm 28 November 2000 to 10:00 am 4 December 2000.

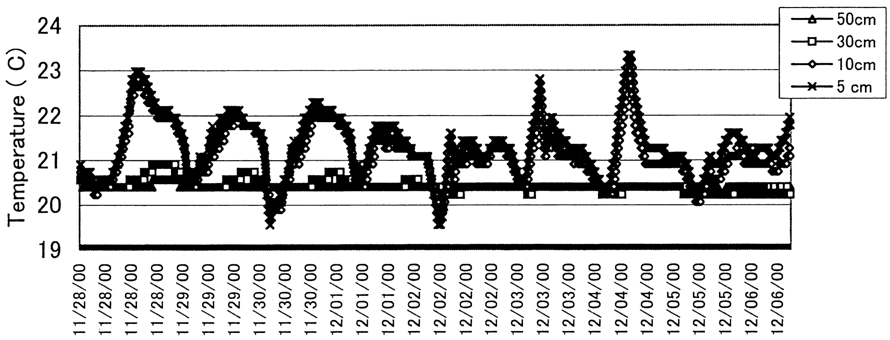

Figure 6. Changes in pore water temperature at the depths of 5, 10, 30 and 50 cm below the seabed.

Subsurface temperature should be treated as a two- or three-dimensional domain because groundwater flow is three-dimensional. However the groundwater flow near the coast, in particular near the seabed, becomes vertical upward (e.g., McBridge and Pfannkuch 1975; Fukuo and Kaihotsu 1988). Therefore, we may treat subsurface temperature as one-dimensional as a first order approximation.

Analytical methods

The equation for steady state, one-dimensional heat conduction–advection in a homogeneous aquifer is;

$$\kappa \frac{\mathrm{d}^2 T}{\mathrm{d}z^2} - c_0 \rho_0 v_z \frac{\mathrm{d}T}{\mathrm{d}z} = 0 \quad [\mathrm{M/LT^3}] \tag{1}$$

where κ is thermal conductivity, T is groundwater temperature, v_z is vertical groundwater flux, and $c_0\rho_0$ is the heat capacity of the water.

To evaluate one-dimensional groundwater flux from borehole temperature, Bredhoeft and Papadopulos (1965) developed type curves based on a steady heat conduction–advection equation. This type curve method was applied to estimate one-dimensional vertical or horizontal groundwater fluxes (Stallman 1965; Boyle and Saleem 1979; Jessop and Vigrass 1989; Lu and Ge 1996). Their type curves are described as;

$$\frac{T - T_0}{T_L - T_0} = \frac{\exp(\beta z/L) - 1}{\exp(\beta) - 1} \quad [1] \tag{2}$$

where L is length of vertical section, $T = T_0$ at $z = 0$, $T = T_L$ at $z = L$, and $\beta = c_0\rho_0 v_z L/\kappa$. Therefore, we can estimate the vertical groundwater flux, v_z, by matching observed borehole temperature profiles to type curves to obtain values of the non-dimensional parameter β. Assuming values for κ, c_0 and ρ_0, the vertical groundwater flux is calculated as;

$$v_z = \frac{\kappa\beta}{c_o\rho_0 L} \quad [\mathrm{L/T}] \tag{3}$$

On the other hand, unsteady subsurface temperature in response to one-dimensional non-isothermal flow of an incompressible fluid through homogeneous porous media is described by;

$$\kappa \quad \frac{\partial^2 T}{\partial z^2} - c_0\rho_0 v_z \frac{\partial T}{\partial z} = c\rho \frac{\partial T}{\partial t} \quad [\mathrm{M/LT^3}] \tag{4}$$

where $c\rho$ is the heat capacity of both fluid and solid phases. Suzuki (1960) and Stallman (1965) developed the analytical solution of (4) for a semi-infinite aquifer under the assumption of sinusoidal change at z_0 in the form

$$T - T_{z0} = \Delta T \exp^{-az} \sin\left(\frac{2\pi t}{\tau - bz}\right) \quad [\theta] \tag{5}$$

where T_{Z0} is the mean temperature at the upper boundary $z = 0$, ΔT is the amplitude of temperature variation at the upper boundary, τ is the corresponding period of temperature oscillation, and a and b are constants. Stallman (1965) solved for a in (5) and found that

$$a = \left[\left(\frac{K^2 + V^4}{4}\right)^{1/2} + \frac{V^2}{2}\right]^{1/2} - V \quad [\mathrm{L}^{-1}] \tag{6}$$

where

$$K = \frac{c\rho\pi}{\kappa\tau} \quad [\mathrm{L}^{-2}] \tag{7}$$

$$V = \frac{v_z c_0 \rho_0}{2\kappa} \quad [\mathrm{L}^{-1}] \tag{8}$$

Taniguchi (1993) introduced a dimensionless parameter β' defined as

$$\beta' = \frac{V}{2K^{1/2}} \quad [1] \tag{9}$$

and developed type curves with various β' to evaluate the vertical water fluxes, v_z, according to

$$v_z = \frac{\beta'(8\kappa c\rho\pi/\tau)^{1/2}}{c_0\rho_0} \quad [\mathrm{L/T}] \tag{10}$$

Estimations of groundwater discharge rates using subsurface temperature

To evaluate the groundwater fluxes from borehole temperature–depth profiles, type curve analyses using (1) and (2) were carried out for NH2A and NH1A (Figure 2(a)). Figures 7(a) and (b) show the type curves and observed temperature data for NH1A and NH2A, respectively. The shapes of the temperature–depth profile were convex between 5.5 and 15.5 m below the surface for NH1A, and 6.5 and 18.5 m for NH2A. Gradients were almost constant above and below these depths, excluding groundwater shallower than 4 m below the surface. Therefore, L was estimated to be 10 m for NH1A and 12 m for NH2A. T_0 and T_L for NH1A and NH2A were estimated to be 19.39 °C and 20.47 °C, and 18.71 °C and 20.63 °C, respectively.

As depicted in Figures 7(a and b), the best matching of type curves yielded values of $\beta = -2.8$ for NH1A and $\beta = -3.5$ for NH2A. Setting $\kappa = 1.6\,\mathrm{W}^{-1}\,\mathrm{m}^{-1}$

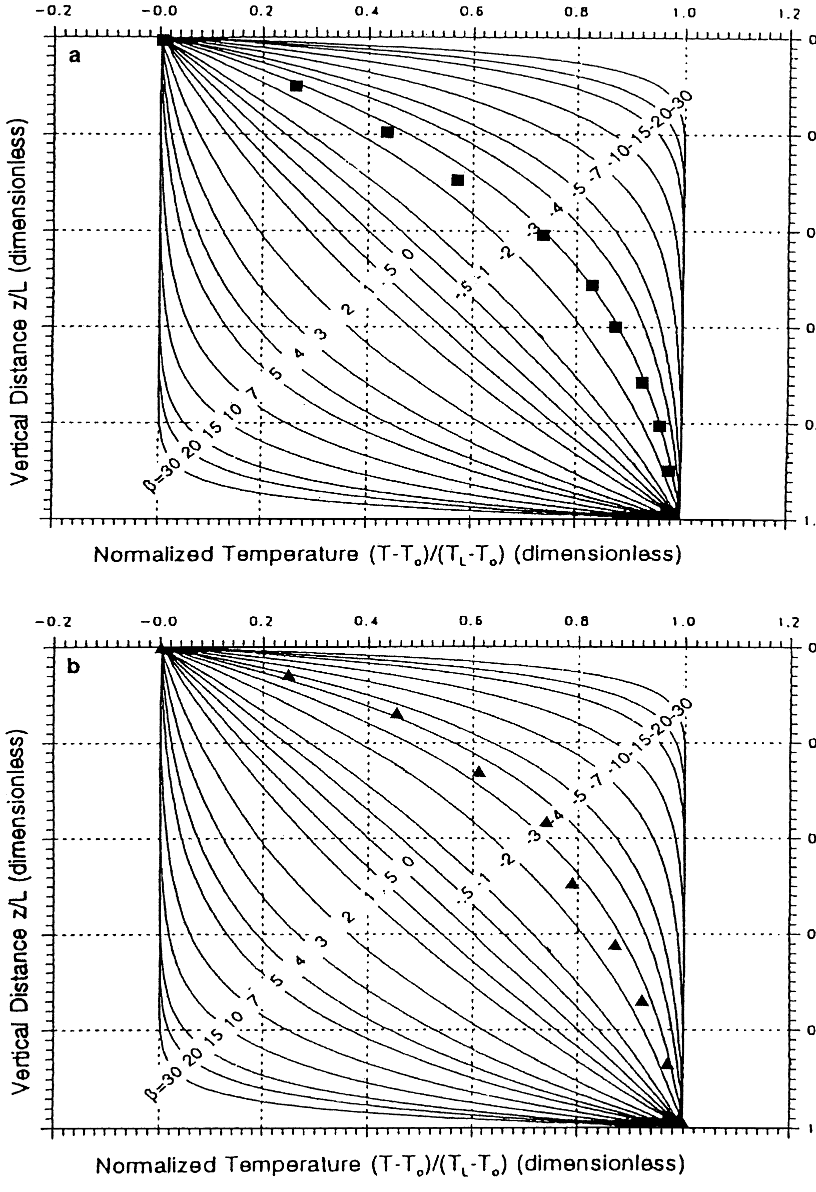

Figure 7. Type curves and observed borehole temperature. For (a) NH1A and (b) NH2A.

and $c_0\rho_0 = 4.18 \times 10^6\,\mathrm{J\,^\circ C^{-1}\,m^3}$, v_z was calculated to be $-0.92\,\mathrm{cm/day}$ (upward flux) at NH1A and $-0.96\,\mathrm{cm/day}$ at NH2A. The thermal property values assumed for sand and applied in this analysis were adopted from Taniguchi et al. (1999a). Taniguchi et al. (1999a) also examined the sensitivity of v_z to variation in $\kappa/c_0\rho_0$

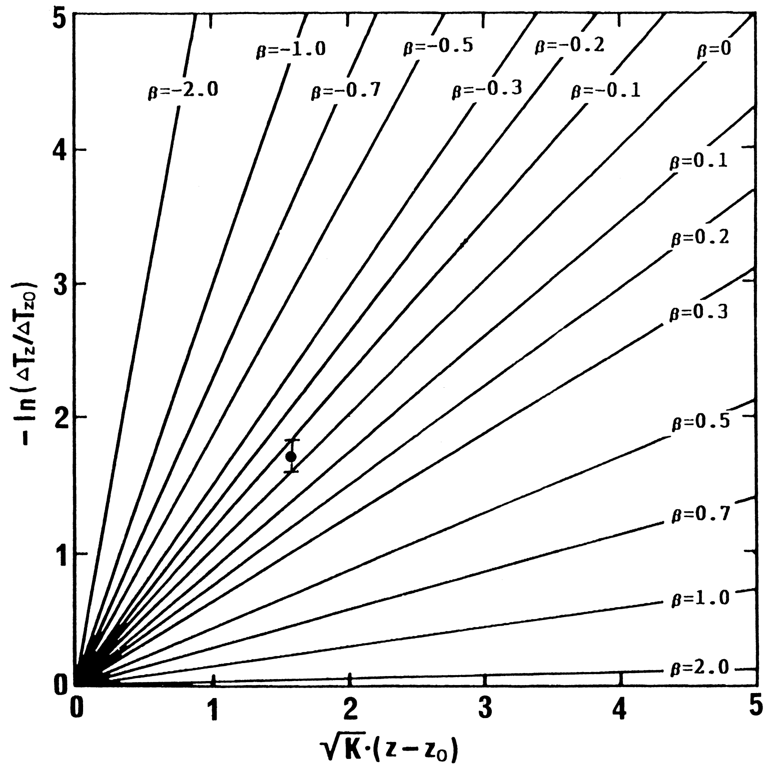

Figure 8. Type curves and observed pore water temperature.

under similar conditions to those experienced in Cockburn Sound, and they concluded the $\kappa/c_0\rho_0$ is not an important parameter for v_z estimations. Because the type-curve method assumes that heat transport is steady state, this analysis is only valid if the measured temperature profile between T_0 and T_L is representative of average temperature.

To evaluate the vertical groundwater flux from continuous pore water temperature data, analyses using type curves developed by Taniguchi (1993) were made by assuming that the change in pore water temperature was sinusoidal in time. Figure 6 indicates that the amplitude of change in pore water temperature decreased with increasing depth, while time lags increased. Because the attenuation of water temperature at 5 and 10 cm below the seabed was small, the data from 10 cm were used to represent temperature at the upper boundary (z_0), and the data from 30 cm were used to represent temperature at depth z.

According to the pore water temperature data at these depths, amplitudes of the diurnal temperature changes at z_0 (10 cm) and z (30 cm) were estimated to be 0.923 and 0.17 °C, respectively. Setting $\tau = 24$ h (86,400 s) and $\kappa/c\rho = 6 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$ for sand (Taniguchi et al. 1999a), the best fitted β' is estimated to be -0.05 (Figure 8, negative β' means upward groundwater flux). The vertical groundwater flux is estimated from (10), $\kappa = 1.6\,\mathrm{W\,^{\circ}C^{-1}\,m^{-1}}$, $c\rho = 2.7 \times 10^{6}\,\mathrm{J\,^{\circ}C^{-1}\,m^{-3}}$ (Taniguchi 1993), and $c_0\rho_0 = 4.18 \times 10^{6} J^{\circ\,-1}\,\mathrm{m^{-3}}$ to be $-4.2 \times 10^{-7}\,\mathrm{m\,s^{-1}}$ ($-3.6\,\mathrm{cm/day}$).

According to the continuous measurements of SGD rates by an automated seepage meter and Lee-type manual seepage meters, the average SGD for each meter during the entire observation period varied in the range of 13.7–16.3 cm/day. Groundwater discharge rates estimated from subsurface temperature in NH1A and NH2A were 0.92 and 0.96 cm/day and SGD estimated from pore water temperature was 3.6 cm/day. Therefore, SGD rates measured by seepage meters were larger than those estimated from subsurface temperature. One explanation is that seepage rates measured by seepage meters may include both terrestrial groundwater discharge and recirculated salt water (Taniguchi et al. 2002). On the other hand, the discharge rates estimated from subsurface temperature may consist of only terrestrial fresh groundwater discharge. Although subsurface temperature cannot indicate whether recirculated seawater is a component of the SGD, temperature difference between pore water and seepage water (Krupa, 2002) may support this argument.

The difference between SGD rates estimated from the pore water temperature at 10 m offshore from the coast and the rates estimated from the temperature–depth profile at 75 and 160 m inland, may be caused by the geographical location of the measurements. According to the SGD analyses by Kohunt (1964), the area that can effectively convey groundwater flow near the coast is smaller than the area that can effectively convey groundwater inland. Therefore, the velocities must increase toward the coast. These estimates also represent the vertical component of the groundwater flow. The landward regions experience predominantly horizontal flow, whereas streamlines of the groundwater at the coast are more vertical, indicating larger vertical components of the velocity.

Conclusions

Our main conclusions are summarized below:

(1) The average of SGD rate, 16.3 cm/day, measured using an automated seepage meter agreed well with the average SGD rate, 13.7 cm/day, measured using manual (Lee-type) seepage meters at E1, which was located 10 m offshore from the coast.
(2) Diurnal variations of SGD due to tidal effects were observed in continuous measurements of SGD made using the automated seepage meter.
(3) Upward groundwater fluxes were estimated from borehole temperature and pore water temperature using type curve methods to be 0.92 and 0.96 cm/day at 75 and 160 m inland from the coast, and 3.6 cm/day at 10 m offshore, respectively.
(4) The SGD estimated from subsurface temperature may consist of only terrestrial fresh groundwater discharge, however SGD rates observed by seepage meters may include both fresh groundwater discharge and recirculated saline water. Therefore, the standard seepage meter measurements of SGD might strongly overestimate freshwater flow from terrestrial origin.

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