Combination of tracer techniques and numerical simulations to evaluate the groundwater capture zone

MAKOTO TANIGUCHI
Department of Earth Sciences, Nara University of Education, Nara 630-8528, Japan
e-mail: makoto@nata-edu.ac.jp

KUNIMITSU INOUCHI
Centre for Cooperative Research and Development, Ehime University, Matsuyama 790-8577, Japan

NORIO TASE & JUN SHIMADA
Institute of Geoscience, University of Tsukuba, Ibaraki 305-8571, Japan

Abstract The groundwater flow system and capture zone were evaluated using the combination of stable isotopes, continuous measurements of groundwater seepage rate, and numerical simulations by a 2-D unsaturated–saturated three-layer model. The $\delta^{18}O$ of the precipitation was used as a tracer to detect the capture zone. The depth of the groundwater which discharges near the lake shore is estimated to be deeper than 100 m below the surface even though the clay layer exists from a depth of 10 to 20 m below the surface. The combination of tracer methods and numerical simulations enabled us to understand the groundwater flow system and the capture zone of the groundwater in the Lake Biwa basin.

INTRODUCTION

Lake Biwa, the largest lake in Japan, has serious water quality problems, including eutrophication. The ratio of groundwater seepage into Lake Biwa to the inflow from rivers is estimated to be more than 0.1 (Taniguchi & Fukuo, 1996). Therefore, it is important not only to evaluate the nutrient discharge into the lake by rivers but also by groundwater.

In order to evaluate the interaction between surface water and groundwater, stable isotopes are widely used (Townly *et al.*, 1991; Shimada *et al.*, 1993; Taniguchi *et al.*, 1995), and the capture zone and release zone are estimated numerically (Nield *et al.*, 1994). The purposes of this study are to evaluate the groundwater flow system in the Lake Biwa basin in terms of nutrient discharge by groundwater, and to estimate the groundwater capture zone using stable isotope tracers and numerical simulations.

STUDY AREA AND OBSERVATION METHODS

Lake Biwa is located in central Japan (Fig. 1). The surface area of the lake is 674 km^2, and its drainage basin area is 3850 km^2. The mean water level of the lake is 85.6 m above sea level, and the maximum depth of the lake is about 103 m. Annual precipitation in the basin is estimated to be 1845 mm.

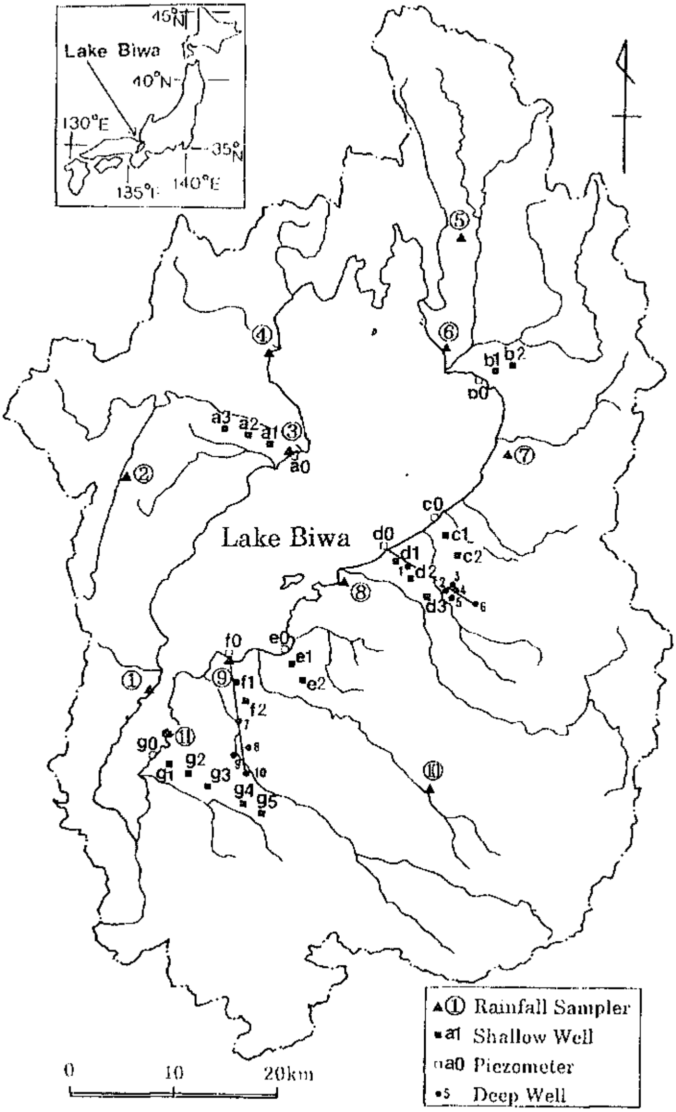

Fig. 1 Location of the study area and sampling points.

The $\delta^{18}O$ and δD of the precipitation were measured at 11 locations (Fig. 1) at monthly intervals from October 1996 to September 1997. In order to evaluate the groundwater flow system and the capture zone of the groundwater into Lake Biwa, the stable isotopes were measured every three months from October 1996 to September 1997, for water discharged from the lake bottom and the groundwater in 19 shallow wells and 30 deep wells along seven observation lines. The groundwater discharged from the bottom of the lake at the near shore of the seven observation lines was collected by piezometers and by using a hand pump. Groundwater seepage rates at f0 (Fig. 1) was measured continuously using automatic seepage meters developed by Taniguchi & Fukuo (1993).

STABLE ISOTOPE RATIOS IN PRECIPITATION

The annual weighted mean of $\delta^{18}O$ in precipitation is shown in Fig. 2. As can be seen from Fig. 2, $\delta^{18}O$ in precipitation decreases in the basin from northwest to southeast. According to wind direction records at 850 hPa near the study area, the prevailing wind direction is northwest during winter and southwest during summer. Therefore, the isotopic depletion in weighted mean of $\delta^{18}O$ in precipitation with increased distance from the Japan Sea is caused by an effect from the Japan Sea during winter, since the Japan Sea is much closer to the basin than the Pacific Ocean.

The δ diagram which is the relationship between $\delta^{18}O$ and δD in precipitation, shows $\delta D = 8\delta^{18}O + 22.1$ in winter and $\delta D = 8\delta^{18}O + 8.8$ in summer. The d excess usually indicates the origin of the precipitation. The precipitation with $d > 20$ seems to

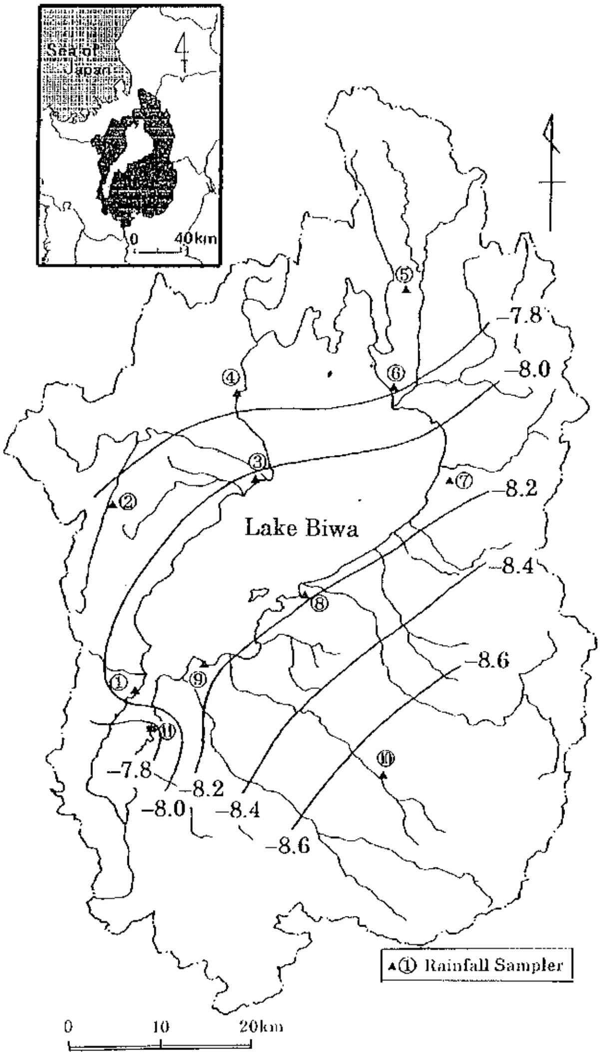

Fig. 2 Weighted mean of $\delta^{18}O$ (‰) in precipitation.

originate from the Japan Sea (Waseda & Nakai, 1983) or over the Eurasian continent (Kondo & Shimada, 1997); and that with d < 10 is from the Pacific Ocean. Therefore, the precipitation in the Lake Biwa basin during the winter season originates either from the Japan Sea or over the Eurasian continent while that in the summer season originates from the Pacific Ocean.

STABLE ISOTOPE RATIOS IN GROUNDWATER

groundwater with low $\delta^{18}O$ moves upward and discharges near the shoreline of the lake. This is the evidence of the regional groundwater flow system. According to Figs 3 and 4, the capture zone of the groundwater is deeper than 100 m below the surface even though a clay layer exists 10–20 m below the surface.

GROUNDWATER SEEPAGE RATE

Continuous measurements of the groundwater seepage rate from the lake bottom have been done at f0 (Fig. 1) using an automatic seepage meter. The daily means of groundwater seepage rate from the lake bottom at f0 ranged between 0.5 and 8.5 × 10^{-7} m s^{-1} during May and October 1994 (Taniguchi, 1995).

Changes in the seepage rate are shown in Fig. 5 at points A (40 m from shore) and B (60 m from shore) for the f0 station (Fig. 1) after precipitation during 4 and 5 December 1996. The near-shore seepage rate is higher than that off shore. The seepage rate increased after precipitation to the order of 10^{-6} m s^{-1}.

NUMERICAL SIMULATIONS OF CAPTURE ZONE

In order to evaluate the change in seepage rate after precipitation, unsteady numerical simulations have been made using a 2-D unsaturated–saturated model with three-

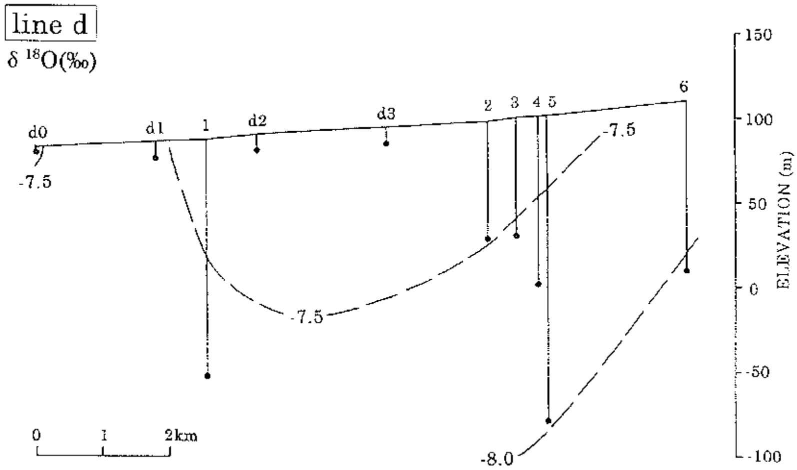

Fig. 3 The $\delta^{18}O$ (‰) in groundwater in the 2-D cross-section of line d.

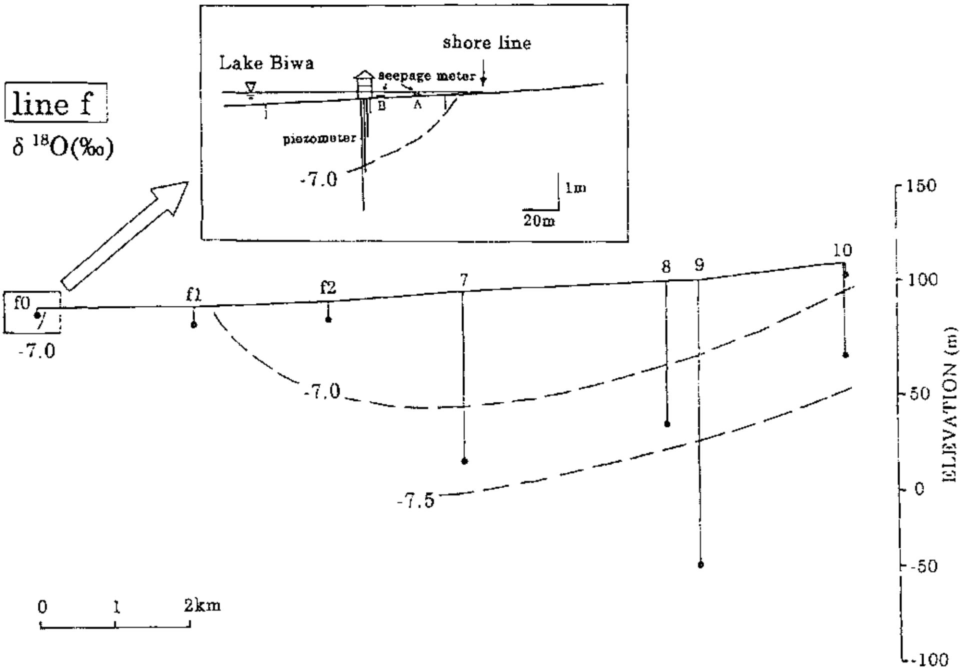

Fig. 4 The $\delta^{18}O$ (‰) in groundwater in the 2-D cross-section of line f.

layers. The governing equations of the water flux are:

$$q = K\{\nabla(\psi + z)\} \tag{1}$$

$$(Cs + Ss)\partial\psi/\partial t + \nabla q = 0 \tag{2}$$

where q is water flux; K is hydraulic conductivity; ψ is pressure head; and Cs and Ss are specific moisture capacity and specific storage, respectively. Simulations have

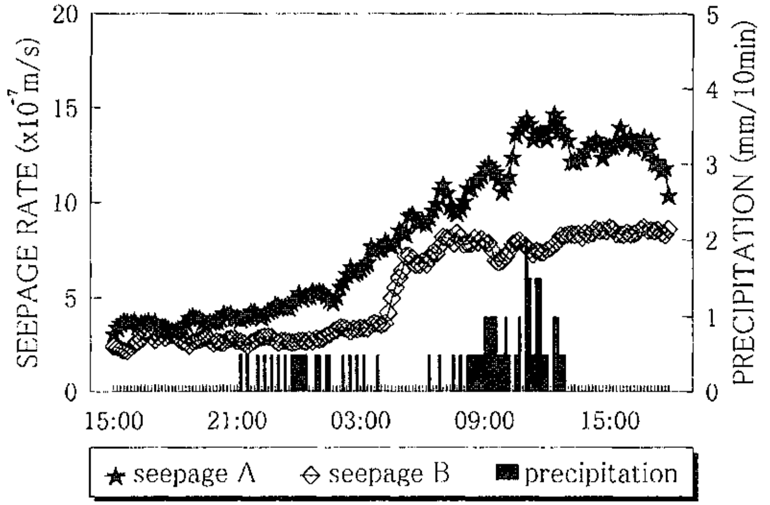

Fig. 5 Changes in groundwater seepage rates at A (near shore) and B (off shore) after precipitation from 4 to 5 December 1996.

been made by the Galerkin finite elements method for space and the finite difference method for time.

Figure 6 shows the vectors of groundwater flux calculated using the three-layer model with (a) d_3 (third layer)= 0; (b) d_3=13 m; and (c) d_3 = 93 m. The thickness of the second layer (clay layer) is estimated to be 7 m from borehole records. The hydraulic

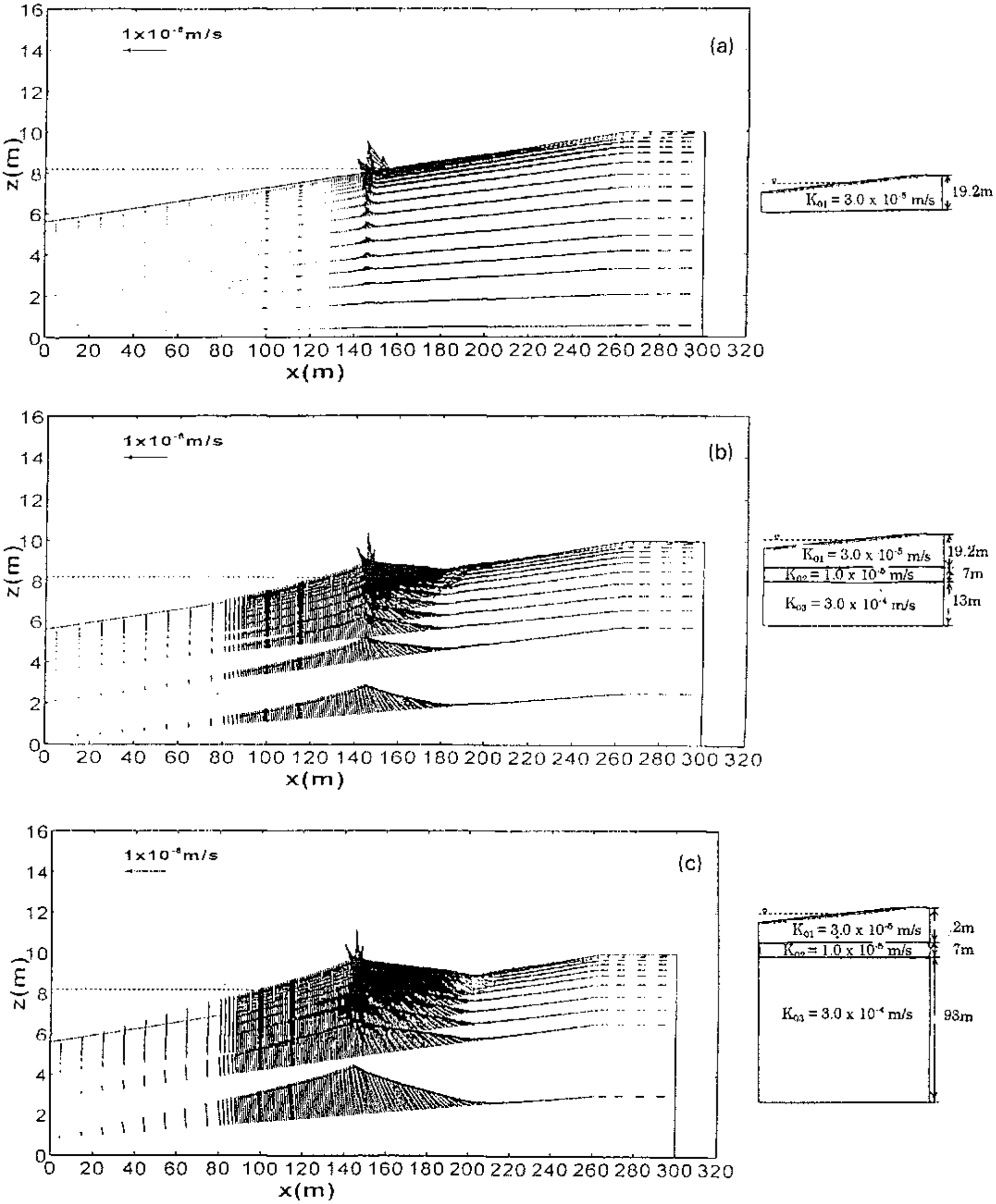

Fig. 6 Calculated vectors of groundwater flux with (a) d_3 (third layer) = 0; (b) d_3 =13 m; and (c) d_3 = 93 m. Right-hand diagrams show the thickness and hydraulic conductivity of each layer.

conductivities, K_{01} (first layer) = 3.0×10^{-5} m s^{-1}; K_{02} (second layer) = 1.0×10^{-5} m s^{-1}; and K_{03} (third layer) = 3.0×10^{-4} m s^{-1} are used for the simulations. When the thickness of the aquifer is set as 110 m with a clay layer (Fig. 6(c)), the simulated seepage rates agree well with the observed rates. Therefore, the capture zone of the groundwater estimated by the numerical simulations also confirms it exists deeper than 100 m below the surface, even though the clay layer exists at a depth of 10–20 m below the surface.

CONCLUSIONS

The conclusions of this study are summarized as follows:

- The groundwater flow system and capture zone are evaluated using stable isotopes in groundwater and precipitation.
- The depth of the groundwater which discharges near the lake shore is estimated by $\delta^{18}O$ and numerical simulation to be deeper than 100 m below the surface even though a clay layer exists from 10 to 20 m below the surface.
- The combination of tracer methods and numerical simulations enable us to understand the groundwater flow system and the capture zone of the groundwater in the Lake Biwa basin.

Acknowledgements The authors wish to thank S. Kunimura, T. Nakayama, D. Kotani, and H. Okano for their assistance in the field. We also acknowledge the Shiga Prefecture Office and Water Resources Public Service for their help. This research was financially supported in part by the Nippon Life Insurance Foundation and the Special Research Project on Global Environmental Change, University of Tsukuba.

REFERENCES

Kondo, A. & Shimada, J. (1997) The origin of precipitation in eastern Asia by deuterium excess. *J. Japan. Soc. Hydrol and Wat. Resour.* **10**(6), 627–629.

Nield, S. P., Townly, L. R. & Barr, A. D. (1994) A framework for quantitative analysis of surface water–groundwater interaction: flow geometry in a vertical section. *Wat. Resour. Res.* **30**(8), 2461–2475.

Shimada, J., Kayane, I., Shimano, Y. & Taniguchi, M. (1993) Use of several environmental tracers to detect the surface–subsurface water interaction in an alluvial fan. In: *Tracers in Hydrology* (ed. by N. E. Peters, E. Hoehn, Ch Leibundgut, N. Tase & D. E. Walling) (Proc. Yokohama Symp., July 1993), 263–274. IAHS Publ. no. 215.

Taniguchi, M. (1995) Change in groundwater seepage rate into Lake Biwa, Japan. *Japan. J. Limnol.* **56**(4), 261–267.

Taniguchi, M. & Fukuo, Y. (1993) Continuous measurements of groundwater seepage using an automatic seepage meter. *Ground Water* **31**(4), 675–679.

Taniguchi, M., Kaihotsu, I. & Kotoda (1995) Isotope studies of precipitation, river water and groundwater in the HEIFE area, northwestern China. *J. Met. Soc. Japan* **73**(6), 1293–1299.

Taniguchi, M. & Fukuo, Y. (1996) An effect of seiche on groundwater seepage rate into Lake Biwa, Japan. *Wat. Resour. Res.* **32**(2), 333–338.

Townly, L. R., Turner, J. V. & Barr, A. D. (1991) Groundwater flow patterns near lakes and wetlands: modelling and field validation. In: *International Hydrology and Water Resources Symposium 1991* (Perth), vol. 3, 732 737.

Waseda, A. & Nakai, N. (1983) Isotopic composition of metric and surface waters in central and northeast Japan. *Earth Chem.* 17, 83–89.