Proceedings of H04, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 361, 2013).

Nutrient transport and surface water–groundwater interactions in the tidal zone of the Yamato River, Japan

SHIN-ICHI ONODERA[1], MITSUYO SAITO[2], MASASHI YOSHIKAWA[1], KOKI ONISHI[1], YUTA SHIMIZU[3] & HIROKO ITO[4]

1 Graduate School of Integrated Sciences, Hiroshima University, 1-7-1 Kagamiyama, Higashi-Hiroshima, Hiroshima, 7398521, Japan
sonodera@hiroshima-u.ac.jp

2 JSPS PD Fellowship, CMES, Ehime University, Matsuyama, Ehime, Japan

3 JSPS PD Fellowship, NARO Western Region Agricultural Research Center, Fukuyama, Hiroshima, Japan

4 Geo-Research Institute, 4-3-2 Itachibori, Nishi, Osaka, 5500012, Japan

Abstract This study examined nutrient transport dynamics and surface water–groundwater interactions in the tidal area of the Yamato River near Osaka, Japan. Spatial variation in radon (^{222}Rn) and hydraulic gradient suggest that groundwater discharges to the river in the upstream reaches, but in the zone near the river mouth, river water recharges the groundwater. The deep groundwater depression is likely due to heavy groundwater extraction for use in Osaka up to 1970. Nitrate-nitrogen (NO_3-N) levels were negatively correlated with dissolved organic nitrogen (DON). Based on mass balance calculations, nutrient production occurred in the tidal reach. Approximately 3% of dissolved total nitrogen (DTN) and 9% of dissolved total phosphorus (DTP) loads were attributed to upstream sources.

Key words nutrient; tidal rivers; groundwater; megacity; Yamato River, Japan

INTRODUCTION

Severe groundwater depression and water pollution have been reported in coastal megacity regions in Asia (Onodera *et al*., 2009; Onodera, 2011; Haque *et al*., 2013). Onodera *et al*. (2009) suggest that groundwater depression is responsible for increasing groundwater pollution due to the intensive percolation of polluted surface water. In the Osaka megacity area, salinization of groundwater is not well documented, because seawater intrusion was not expected to occur at the inland side of the alluvial plane, which is situated far from the coast (Onodera *et al*., 2010). Because seawater intrusion to groundwater from surface water can occur near river mouths in coastal areas (Onodera, 2011), further study of this process has implications for water supply.

Megacities have significant impacts on water quality and quantity in river. For example, the mouth and shallow coastal bay area of the Yamato River has elevated levels of dissolved and particle associated pollutants (Tanimoto & Hoshika, 1997; Hayashi & Yamagi, 2008; Hosono *et al*., 2010; Tsuzuki & Yoneda, 2011). Because of water level fluctuation and freshwater–seawater mixing, nutrient dynamics and surface water–groundwater interactions are complex (Eyre, 2000; Wetz *et al*., 2008; Arndt *et al*., 2011; Schlarbaum *et al*., 2011) and require further study. The objective of this study is to examine nutrient transport dynamics and surface water–groundwater interactions in the tidal zone of the Yamato River, near Osaka, Japan.

METHODS

Study area

Osaka megacity includes the cities of Osaka, Kobe, Kyoto and Sakai, which each have populations of more than one million people. The megacity is the biggest city area in western Japan and the 12th largest in the world. The total population of the Osaka megacity is more than 15 million. The Yamato River is located in the southern area of the megacity and flows along the boundary between Osaka and Sakai City (Fig. 1(a)). The river is 68-km long and drains an area of 1070 km^2. The water quality of the river is poor and is cited as one of the worst in Japan (MLITT, 2013). Before 1980, the BOD was >20 mg/L, but it has recovered to around 5 mg/L since the implementation of sewage systems.

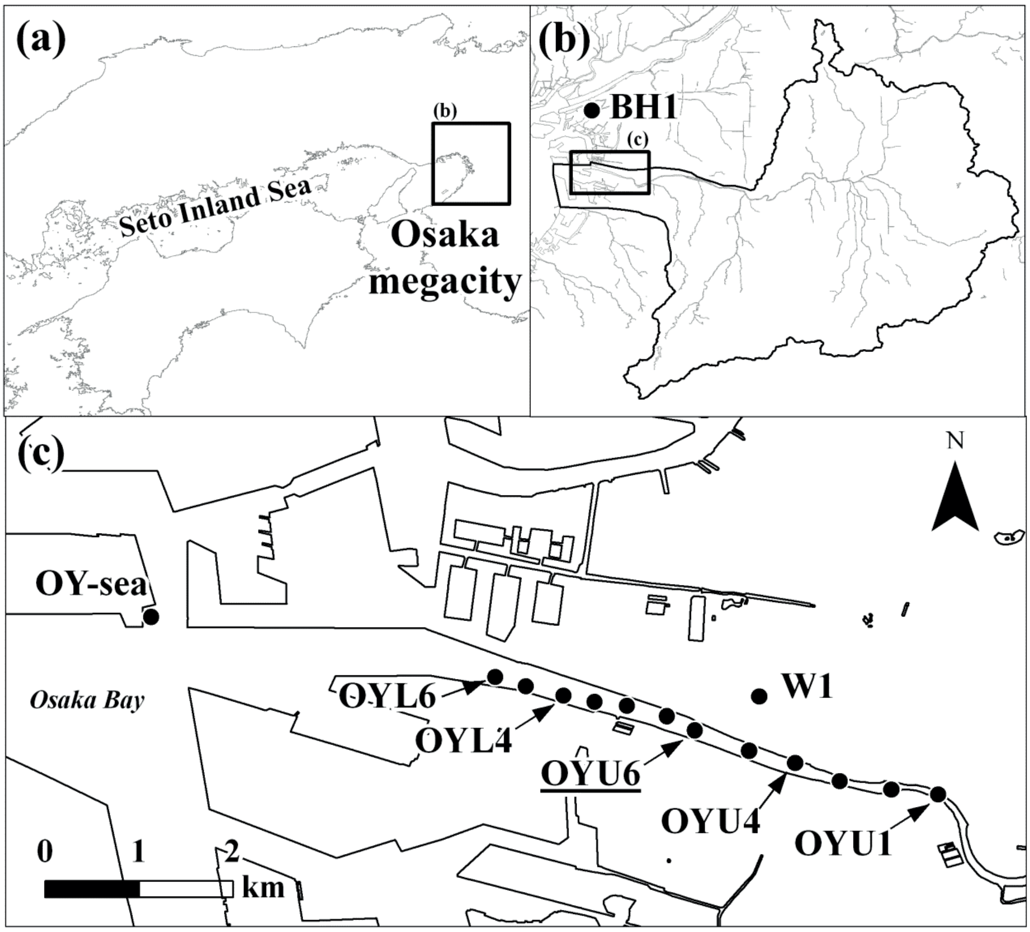

Fig. 1 Location of the study area.

Osaka is situated on an alluvial plain which contains groundwater resources at depths ranging from 50 to 1000 m. Since the 1950s, this subsurface water supply had been used to such an extent that severe land subsidence and lowering of groundwater levels by over 30 m has resulted. Since groundwater withdrawal was regulated in the 1960s, water levels have started to recover. The tidal variation in Osaka Bay is about 1 m in the neap tide and 2 m in the spring tide (Fig. 3) and it causes the river stage to fluctuate from study locations OYL-6 to OYU-4 (Fig. 1(c)). Stations OYL-6 and OYU-1 are also the official monitoring sites for water level, runoff and water quality by the Ministry of Land, Infrastructure, Transportation and Tourism (MLITT, 2013).

Methodology

Water samples were collected in the centroid of the channel at 13 stations from the river mouth (OY-Sea) to 7 km upstream (OYU-1), on the Yamato River (Fig. 1(c)). Water samples were analysed for nutrients (NH_4^+, NO_2^-, NO_3^-, dissolved inorganic phosphorus (DIP), dissolved silica (DSi), dissolved total nitrogen (DTN) and dissolved total phosphorus (DTP)) using an auto-analysing system (swAAt, BLTEC) of standard absorption photometry, for dissolved organic carbon (DOC) using a total organic carbon analyser (TOC-Vcsh/csn, SHIMADZU) and inorganic ions using ion chromatography (LC20ad, SHIMADZU). To assess spatial variations in ground-water discharge, radon (^{222}Rn) concentrations of river water and hydraulic gradients between subsurface water and river water were measured. Radon measurements were carried out *in situ* at the same stations as water collections, using RAD Aqua Systems (RAD7, Durridge Co.) by the method of Burnett & Dulaiova (2003). The hydraulic head observations of subsurface water were conducted using piezometers installed to 1 m depth in the centroid and side of the channel at

OYU-1, OYU-4, OYU-6, OYL-4 and OYL-6. They are 50 mm slotted PVC pipes of 40 mm diameter. The subsurface water samples were also collected from the piezometers at all stations for nutrient analysis and radon measurements. Water samples were filtered through disposable 0.2 µm filters and were kept in the freezer until the nutrient analysis.

In addition, temporal variation in radon, chlorophyll and electrical conductivity of river water, water levels of river and piezometers, and river velocity were monitored at OYU-6 during intensive observation periods for about one week in September 2011 and 2012, and January 2013, using a RAD7 system, light sources (LEDs) of chlorophyll sensors (INFINITY-CLW, JFE Advantech), CTD sensors (CTD-Diver, SWS), and ADCP (WH-Sentinel, Teledyne RD Instruments). To confirm the variations in nutrient concentration, water samples were collected at intervals of one hour during these periods.

Groundwater level datasets in and around Yamato River were collected at W1 (Fig. 1(c)) installed in shallow unconfined groundwater, and at BH1 (Fig. 1b) which is confined groundwater at a depth of 25 m.

RESULTS AND DISCUSSION

Recent groundwater status

Figure 2 shows the temporal variation in piezometric head from 1983 to 2010 at BH1. The data show that groundwater levels have recovered since 1960, and by 20 years later it had risen considerably. However, it still keeps remains below 0 m O.P., which is the minimum tidal level in Osaka Bay. In addition, the confined groundwater which is >100 m deep has a lower hydraulic head than that in BH1. These results indicate that seawater intrusion to the coastal groundwater still occurs (Onodera *et al.*, 2010). However, the shallow groundwater level at W1 was obviously higher than the river water level. It suggests that shallow groundwater discharges to the river.

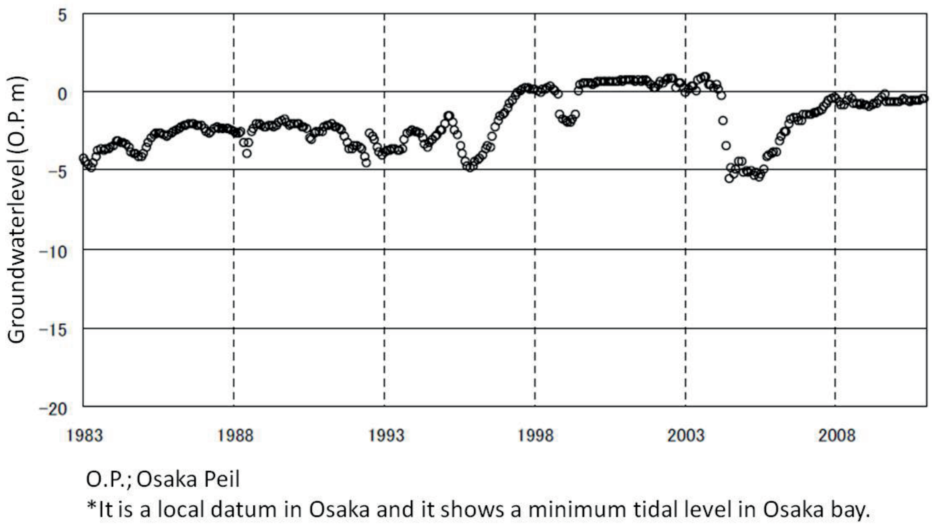

Fig. 2 Piezometric head variation from 1982 to 2010 at BH1 with a depth of 25 m.

River water–groundwater interaction

The temporal variations in river water levels and differences of hydraulic potential between river water and the porewater for 13–17 September in 2012 at OYU-1 and OYU-6 are shown in Fig. 3. When the difference in Fig. 3 is negative, it corresponds to periods when groundwater discharges to the river. The river water level data show the effect of the semidiurnal variation of tidal fluctuations at OYU-6 and the rise in the afternoon on 14 September at OYU-1 due to flooding. The data suggest that river water is seeping into groundwater at OYU-6, but groundwater is discharging into the river at OYU-1. The trend of river water seepage was also confirmed in the

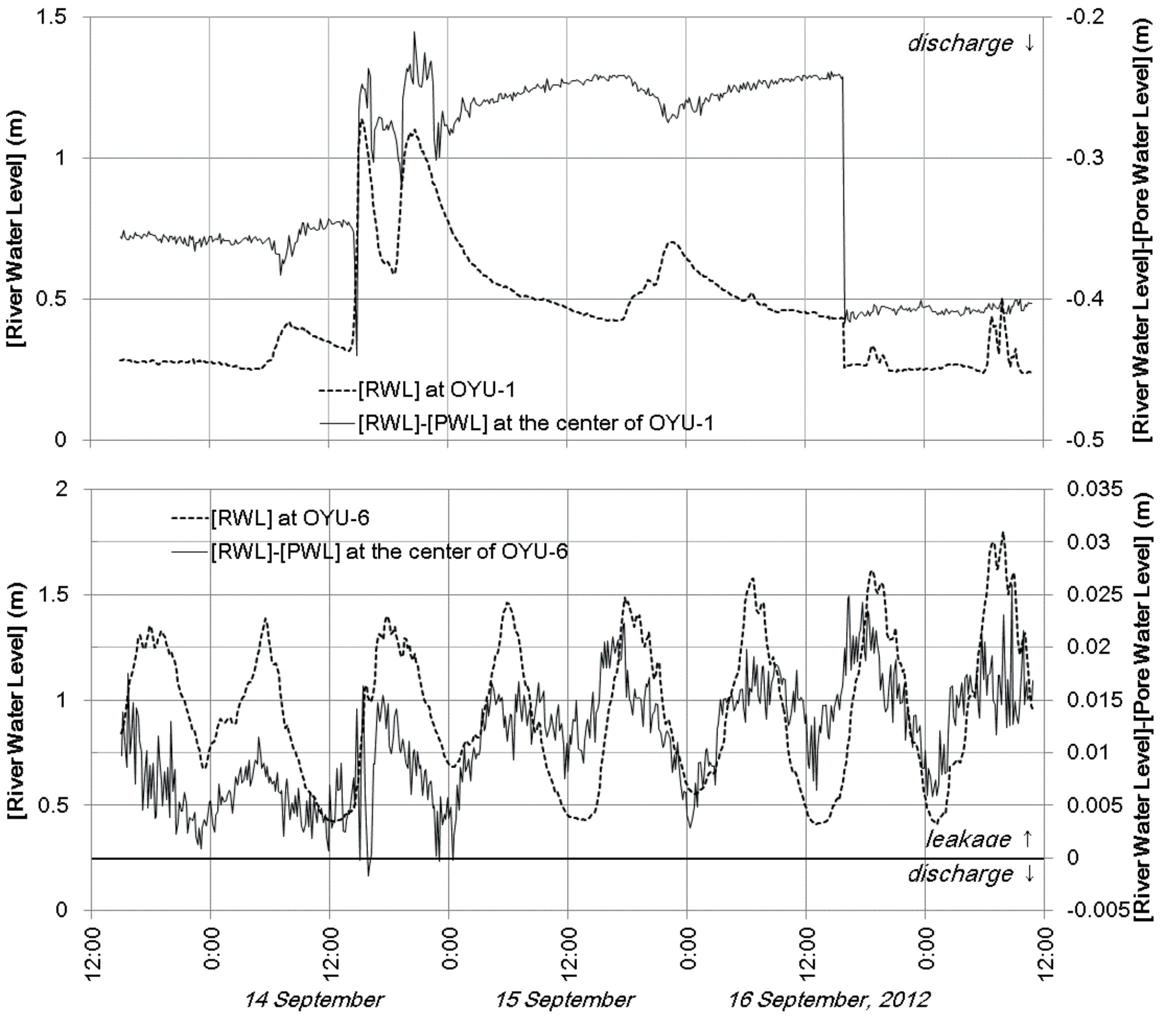

Fig. 3 Temporal variations in river water levels and differences of hydraulic potential between river water and the pore water, 13–17 September 2012, at the centre of the channel for OYU-1 and OYU-6.

centroid at OYU-4 and OYU-6 and at the side at OYL-6, whereas the trend of groundwater discharge was confirmed only at OYU-1. At the river side plots of OYU-4, OYU-6 and OYL-4, both trends of groundwater discharge and river water seepage were confirmed. This suggests a hyporheic exchange of river water and porewater.

Radon (^{222}Rn) has been used as a significant geochemical tracer to detect groundwater discharge into the surface water, because radon values of groundwater are usually from 100 to 1000-fold higher than that of surface water (e.g. Burnett & Dulaiova, 2003). Radon concentrations were higher at OYU-1, but lower at OY-Sea. However, it was much higher in porewater than that in the river water. Observed changes in hydraulic head and radon levels indicate that groundwater discharges to the river channel in the upstream area. The groundwater discharge into the tidal river has been previously reported by Peterson *et al*. (2010) and Santos *et al.* (2012). In contrast, the results of the present study show that in tidal reaches near the river mouth, saline river water is recharging groundwater. This would be caused by the hydraulic head depression in the confined groundwater (Fig. 2). The significant lowering of water level was caused by intensive groundwater extraction during the developing period of Osaka megacity, from the 1950s to the 1960s. Groundwater recharge by saline river water in many channels, including the Yamato River, in the coastal zone would expand the groundwater salinization area in Osaka.

Figure 4 shows the relationship between the river water level and radon concentration in river water at OYU-6 from 28 to 29 September 2011. The radon concentration tends to increase by

1.5 times the lowest value during the lower river water level period. The values were from 2 to 10 times higher in porewater than those in river water at all stations. But, the hysteresis of this relationship was indicated; the radon concentration remained a little bit higher during a rising period of the water level after a low tide. This result suggests that groundwater with high radon discharges to the river during the low tide, and river water seeps into groundwater during the high tide, that is recirculation of river water and the hyporheic exchange between river water and subsurface water. The piezometric data also supported this trend. This hyporheic exchange would affect nutrient transport in the tidal river.

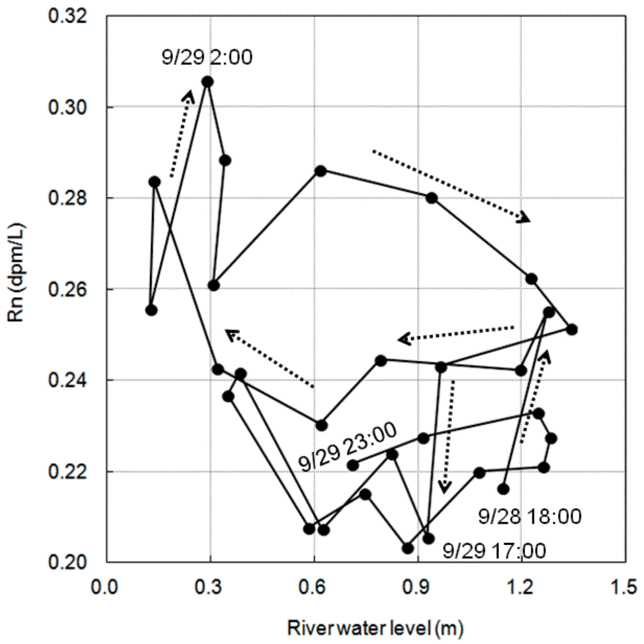

Fig. 4 Relationship between the river water level and radon concentration at OYU-6 from 28 to 29 September 2011.

Nutrient transport in a tidal river

Figure 5 shows the time-series variation in the river water level (a), ^{222}Rn (b), DIN (c), DIP (d) and DSi (e), at station OYU-6 from 28 to 30 September 2011. Water level changed with the tidal fluctuation. ^{222}Rn concentration showed a slightly increasing trend during the low water level period. It suggests increase of groundwater discharge to the river. Nutrient concentrations fluctuated from about 90 to 210 μmol/L in DIN, from 6.5 to 9 μmol/L in DIP, and from 200 to 290 μmol/L in DSi.

Figure 6 shows the nutrient differences between that in the upstream (OYU-2) and in the downstream (OYU-6), which is tidally-forced area. The variations are shown as the relation between ΔNO_3-N and ΔNH_4-N (a), ΔDTN (b), and ΔDON (c), respectively. There are no tributary confluences or sewage outlets to the river between the two stations. These temporal changes in nutrient differences depend on the time-series nutrient variation from OYU-4 to OYU-6 due to tidal variation (Fig. 1(c)), because the nutrient concentrations and runoff were almost constant at OYU-1 during the intensive observation period. The positive value indicates nutrient concentration increased from OYU1 to OYU6, that is nutrient production occurred in the tidally-forced area, while the negative value indicates nutrient attenuation occurred. Solid arrows in Fig. 6 represent the biogeochemical processes related to nitrogen production and attenuation of respective fractions. Figure 6 indicates that ΔNH_4-N shows little change compared with ΔNO_3-N (a). ΔDTN totally increases with ΔNO_3-N variation but some of them decrease with NO_3-N attenuation (b). ΔDON shows the clear increasing trend with NO_3-N attenuation (c). These results suggest that two processes occur in the tidally-forced area: (1) DON production by decomposition of sediment

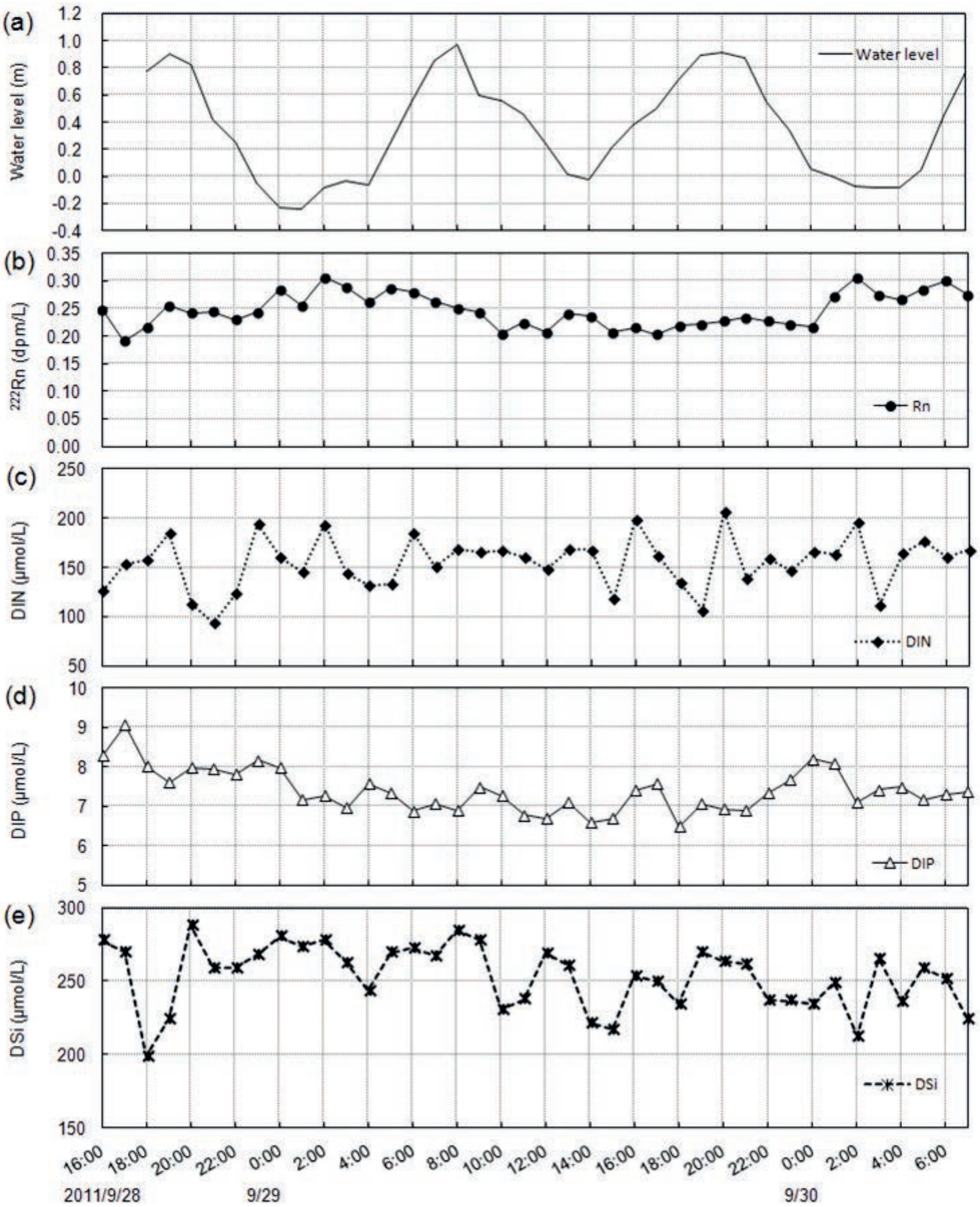

Fig. 5 Time-series variation in the river water level (a), concentrations of ^{222}Rn (b), DIN (c), DIP (d) and DSi (e), at station OYU-6, 28–30 September 2011.

organic matter (Cook *et al*., 2004; Schlarbaum *et al*., 2011) and release from phytoplankton (Bronk, 1999; Wetz *et al*., 2008), and (2) denitrification process induced by the increase of DON as an electron donor, which eventually caused the attenuation of NO_3-N, DON and DTN.

Based on the mass balance estimation, nutrient production from the sediment organic matter in the river bed was suggested in the tidal reach. It was estimated to be 3% of total nitrogen and 9% of phosphorus loads from the upstream (Table 1).

Table 1 Mass balance estimation of nutrients in the tidal reach (*nutrient production (+) and attenuation (-) from OYU-1 to OYU-6).

	DIN	DON	DTN	DIP	DOP	DTP
ΔNutrient* (g d^{-1} km^{-2})	–510	+682	+166	+8	+8	+41
(ΔNutrient) / (Nutrient flux at OYU1) (%)	–10	+105	+3	2	+54	+9

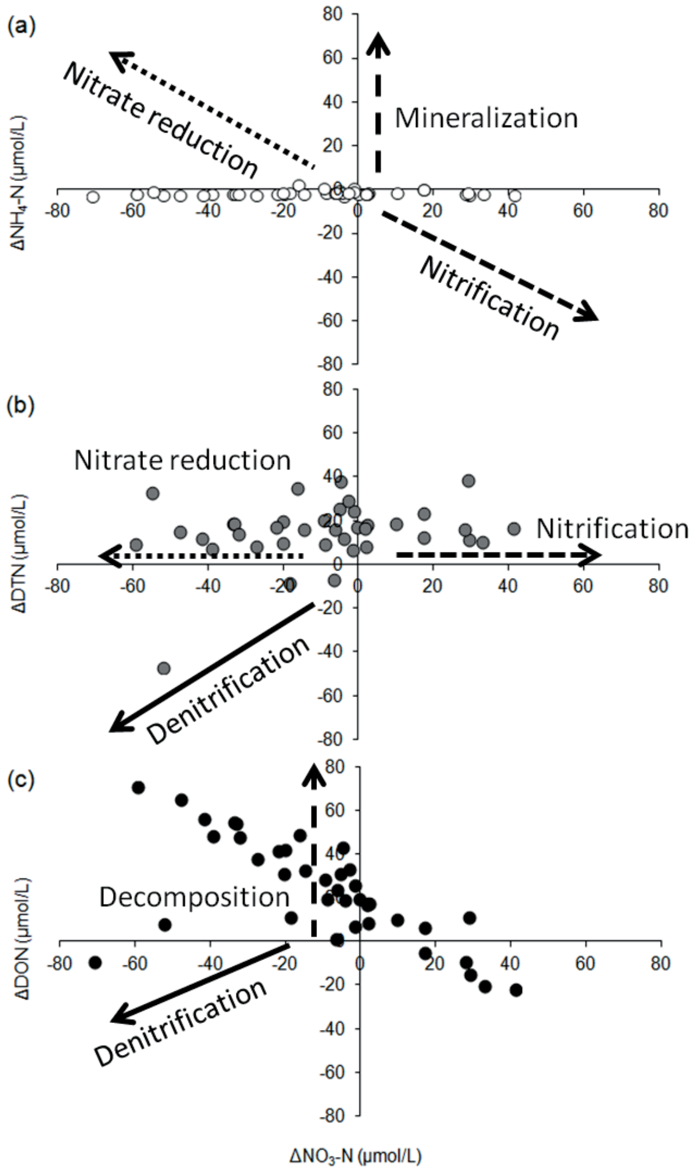

Fig. 6 Nutrient differences between that in the upstream (OYU-2) and in the downstream (OYU-6) which is a tidally-forced area.

CONCLUDING REMARKS

A field survey was conducted to examine nutrient transport and river water–groundwater interactions in the tidal zone of Yamato River. Spatial variation in radon (^{222}Rn) concentrations and the difference of hydraulic potential between river waters and the porewaters suggest that groundwater discharges to the river channel in the upstream area, but recharges groundwater near the river mouth. This may result from the lowering of the groundwater level induced by the excess abstraction in the urban area. The result also implies the seawater intrusion would accelerate the salinization of groundwater. The spatial and temporal variations in nutrient concentrations indicated that NO_3-N concentrations changed temporally and are negative correlated with dissolved organic nitrogen DON concentrations. Based on the mass balance, nutrient production from the river bed was suggested in the tidal reach. That was estimated to be 3% of total nitrogen and 9% of phosphorus loads from the upstream.

REFERENCES

Arndt, S., Lacroix, G., Gypens, N., Regnier, P. & Lancelot, C. (2011) Nutrient dynamics and phytoplankton development along an estuary–coastal zone continuum: A model study. *Journal of Marine Systems* 84, 49–66.

Bronk, D.A. (1999) Rates of NH_4^+ uptake, intracellular transformation and dissolved organic nitrogen release in two clones of marine Synechococcus spp., *Journal of Plankton Research* 21, 1337–1353.

Burnett, W.C. & Dulaiova, H. (2003) Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements. *Journal of Environmental Radioactivity* 69, 21−35.

Cook, P.L.M., Eyre, B.D., Leeming, R. & Butler, E.C.V. (2004) Benthic fluxes of nitrogen in the tidal reaches of a turbid, high-nitrate sub-tropical river. *Estuarine, Coastal and Shelf Sciences* 59, 675–685.

Eyre, B.D. (2000) Regional evaluation of nutrient transformation and phytoplankton growth in nine river-dominated sub-tropical east Australian estuaries. *Marine Ecology Progress Series* 205, 61–83.

Haque, J.S., Onodera, S. & Shimizu, Y. (2013) An overview on the urbanization response to the quantity and quality of groundwater in South Asian megacities. *Limnology* (accepted).

Hayashi, M. & Yamagi, T. (2008) Analysis of change of red tide species in Yodo River estuary by the numerical ecosystem model. *Marine Pollution Bulletin* 57, 1−5.

Hosono, T., Chih-Chieh, S., Okamura, K. & Taniguchi, M. (2010) Historical record of heavy metal pollution deduced by lead isotope ratios in core sediments from the Osaka Bay, Japan. *Journal of Geochemical Exploration* 107, 1–8.

Ministry of Land, Infrastructure, Transportation and Tourism (MLITT) (2013) *Current Situations of River Water Quality*. http://www. mlit. go.jp/report/press/mizukokudo03_hh_000534.html (in Japanese).

Onodera, S., Saito, M., Sawano, M., Hosono, T., Taniguchi, M., Shimada, J., Umezawa, Y., Lubis, R.F., Buapeng, S. & Delinom, R. (2009) Effect of intensive urbanization on chemical environment in deep groundwater; example in Bangkok and Jakarta. *Science of the Total Environment* 407, 3209–3217.

Onodera, S., Shimizu, Y., Arimoto, H. & Nakaya, S. (2010) Nutrient discharge and its long term variation via groundwater to Osaka bay. *Seto Inland Sea*, 60, 62–65 (in Japanese)

Onodera, S. (2011) Subsurface pollution in Asian megacities. In: *Groundwater and Subsurface Environment in Asia* (ed. by Taniguchi, M.), Springer, 159–184.

Peterson, R.N., Santos, I.R. & Burnett, W.C. (2010) Evaluating groundwater discharge to tidal rivers based on a Rn-222 time-series approach. *Estuarine, Coastal and Shelf Sciences* 86, 165–178.

Schlarbaum, T., Dähnke, K. & Emeis, K.(2011) Dissolved and particulate reactive nitrogen in the Elbe River /NW Europe: a 2-yr N-isotope study. *Biogeosciences* 8, 3519–3530.

Santos, I.R., Cook, P.L.M., Rogers, L., Weys, J.de & Eyre, B.D. (2012) The "salt wedge pump": Convection-driven pore-water exchange as a source of dissolved organic and inorganic carbon and nitrogen to an estuary. *Limnology and Oceanography* 57, 1415−1426.

Tanimoto, T. & Hoshika, A. (1997) Transport of total suspended matter, particulate organic carbon, organic nitrogen and phosphorus in the inner part of Osaka Bay. *Journal of Oceanography* 53, 365−371.

Tsuzuki, Y. & Yoneda M. (2011) Pollutant runoff yields in the Yamato-gawa River, Japan, to be applied for EAH books of municipal wastewater intending pollutant discharge reduction. *Journal of Hydrology* 400, 465−476.

Wetz, M.S., Hales, B. & Wheeler, P.A. (2008) Degradation of phytoplankton-derived organic matter: Implications for carbon and nitrogen biogeochemistry in coastal ecosystems. *Estuarine, Coastal and Shelf Sciences* 77, 422–432.