Evaluation of groundwater qualities in a paddy-dominated alluvial fan


ABSTRACT

Analytically assessing groundwater quality is indispensable for sustainable use of groundwater and its effective pollution controls. A large volume of groundwater is stored in the Tedori River alluvial fan, one of which of the predominant land uses being irrigated paddy fields. Much groundwater under the fan is used for drinking and industrial purposes. For assessing agricultural activities at the paddy and upland fields on groundwater quality during an irrigation period, multiple water quality items were measured in several water types, including groundwater, river water, and paddy water. Water quality indicators, such as major dissolved ions, a number of trace elements, and some isotopes were measured. The concentrations of nutrients and some elements related to the environmental standards indicated that pollution in the groundwater in the fan was not severe. Concentrations of the tracers (Mg, Na, δD, δ18O) in the shallow groundwater were low along the Tedori River and increased with distance from the river; this trend would be caused by dilution effect by the river water. It was also shown that the paddy field also affects groundwater quality by the infiltration of irrigation water.

Key words | groundwater quality, groundwater–river water interaction, irrigated paddy field, multi-tracer

INTRODUCTION

The alluvial fan is one of the major landforms in Japan where wide areas of paddy fields exist. It is recognized that water infiltration from the paddy fields to groundwater during irrigation periods contributes significantly to groundwater recharge. In Japan, paddy-upland crop rotation has been conducted at approximately 30% of the total paddy field area. Large amounts of fertilizer and irrigation water are applied to these agricultural fields. In an alluvial fan, groundwater–river water interaction, namely water exchange between the groundwater and river water through the riverbed (river water infiltration to groundwater and groundwater flow to the river), continually occurs due partly to the relatively high conductivity of alluvial deposits. Furthermore, the permeable characteristics strengthens anthropological impact on the groundwater quality. Assessing the water qualities in the groundwater and sources of groundwater, and the relationship among the different waters are important to maintain sustainable groundwater use and to control groundwater pollution.

The Tedori River alluvial fan located in the center area of the western coast of Japan with a total area of 140 km² and a total population of 0.8 million has abundant groundwater storage. The groundwater in the fan is an important water resource for drinking and industrial uses. In the study area, some researchers have examined the interactions between groundwater and river water, which have focused on both river water infiltration to groundwater and groundwater flow to the river through hydrological observations (Futamata et al. 2005; Tsujimoto et al. 2005; Morita et al. 2008; Iwasaki et al. 2015b). Maruyama et al. (2012, 2014)
estimated the water balance in the study area. Ishida & Tsuchihara (2013) investigated the river water contribution ratios to shallow groundwater by end member mixing analysis based on oxygen and hydrogen isotopes, and the age of shallow and deep groundwater using tritium. Hayase (2013) pointed out that a large amount of snowmelt runoff contributed to lowering the concentrations of nitrogen in groundwater and that paddy irrigation water had only a little effect on the nitrogen concentration in groundwater. Yonebayashi & Minami (2013) examined groundwater quality using cluster analysis and a nitrogen isotope. They reported that domestic sewage and livestock wastewater had little contribution to groundwater quality, and groundwater quality in the fan was categorized spatially by the cluster analysis, which were similar to the geographic sections. Iwasaki et al. (2013b, 2014) assessed factors influencing groundwater level change with steady state and transient state numerical flow simulations developed based on observed groundwater level contour maps and the measured water flow between groundwater and the river. However, only a few studies have been conducted on examination of the water quality of shallow groundwater and hydrological water cycle under the irrigated paddy fields. In addition, hydrochemical formation mechanism of groundwater in the alluvial fan is complicated and is not been well-understood. For addressing the above-mentioned issue, this study investigated actual groundwater quality situation utilizing a multi-tracer technique in a paddy-dominated Tedori River alluvial fan in Japan.

**MATERIALS AND METHODS**

**Study area**

The study site is the Tedori River alluvial fan in Ishikawa Prefecture, Japan. This study mainly focuses on the groundwater quality in the right bank of the Tedori River (140 km²). The population in the study area is about 0.8 million. The study area is bounded by the Sea of Japan to the west, the Sai River to the north, the Hakusan Mountains to the east, and the Tedori River to the south. The elevation of the top of the fan is about 80 m asl and the average slope in the fan is 1/140. **Figure 1** illustrates the land use conditions in 2009 using 100 m mesh data. The area consists of paddy, upland, building, and other land covering 45%, 2%, 39%, and 14% of the total, respectively. The rate of paddy rice-upland crop rotation was 25% in the study area. The rice irrigation period in the study area is from mid-April to early September. Rice is planted at the beginning of May and a mid-summer drainage is conducted during June to temporarily dry the paddy soils. In paddy fields, growers typically adopt the rice-upland crop rotation system, in which soybean is grown from June to October and barley from November to May. There has been substantial expansion of urban areas in the north-east part of the fan. The paddy irrigation water is allocated from the Tedori River at the top of the fan.

**Groundwater environments**

A substantial increase of the groundwater level was observed in several continual monitoring wells from the end of April to early May (the beginning of the irrigation period). Changes in groundwater levels at the beginning of the irrigation period are closely linked with the area of paddy fields around the interest groundwater well (Iwasaki et al. 2013a). Groundwater level contours were obtained from simultaneous groundwater-level observations, which were conducted at 113 wells in December 1993, 87 wells in November 2009, and 86 wells in June 2010. Comparisons of the groundwater levels between the irrigation period in 2010 and the non-irrigation period in 2009 revealed that
the water level during the irrigation period was 5 m higher than that during the non-irrigation period. The results indicated that the groundwater recharge from the paddy field affected the groundwater levels in the study area. In addition, the groundwater level during the non-irrigation period declined 5 m during 1993–2009 due to the decrease of paddy field area (Iwasaki et al. 2013b).

In the study area, the water exchange between shallow groundwater and the Tedori River water was quantified by on-site observation. Figure 2 shows the amount of net water exchange through the river bed. In the irrigation period in 2009, groundwater flowed to the river (gaining river) in the downstream section located between 1.1 and 2.2 km from the river mouth, and the river water infiltrated predominantly into the groundwater in the section located between 2.2 and 16.4 km from the river mouth except the section from 11.8 to 14.3 km (Iwasaki et al. 2013b).

Groundwater use

There are many business entities over the fan (including food factories, breweries, and precision machine factories), which use large volumes of clean groundwater. Annual groundwater use in the fan was estimated as $1.0 \times 10^9$ m$^3$/year in 2008 (Ishikawa Prefecture 2010). The proportion of groundwater use for industrial, drinking, snowmelt, irrigation, and building maintenance in 2005 were 59%, 30%, 4%, 4%, and 5%, respectively. The groundwater is used for irrigating the upland fields primarily only in the coastal zone near the Sai River. Some cities in the fan rely on groundwater as drinking water.

Sampling method and water quality analysis

Water samples were taken in the irrigation period of June in 2011 for 63 groundwaters, two spring waters, 13 river waters, and five paddy ponding waters. River water samples were collected from the Tedori River and the Sai River, including some branches in lowland and hinterland areas of the basin. This paper focuses mainly on water quality in the fan. Figure 3 shows the locations of the water sampling points in the fan.

The water quality analysis items were water temperature, electrical conductivity (EC), pH, NH$_4$-N, NO$_3$-N, NO$_2$-N, total nitrogen (T-N), PO$_4$-P, total phosphorus (T-P), total organic carbon (TOC), major ions (Na, K, Ca, Mg, Cl, and...
SO\(_4^2\)\), trace elements which are of common environmental interest, and oxygen and hydrogen isotopes. Major cation and anion concentrations, NO\(_3^--\)N, and NO\(_2^-\)N were analyzed by ion chromatography (LC-10A, Shimadzu Corp., Japan). A large number of elements (Cd, Cr, Se, Pb, As, B, Zn, Al, Fe, Cu, Mn, Sb, Ni, Ba, Mo, Li, and Sr) were determined by inductively coupled plasma–mass spectrometry (ICP-MS) (7500cx, Agilent Technologies, USA). The oxygen and hydrogen isotopes (hereafter called \(\delta^{18}O\) and \(\delta D\), respectively) values were determined using a water isotope analyzer (L2120-I, Picarro, Inc., USA).

RESULTS AND DISCUSSION

Figure 4 shows mean concentrations of NO\(_3^--\)N, NH\(_4^+\)-N, T-N, PO\(_4^{3-}\)-P, T-P, and TOC related to nutrients in the groundwater, river water, and paddy water. The NO\(_3^--\)N concentration in all the water samples ranged between 2.00 and 2.92 mg/L. The mean NO\(_3^--\)N concentration in the groundwater was higher than those of the river and paddy waters. Relatively low concentration in the paddy water was considered to be affected by less nitrification and/or denitrification effects in the paddy fields. The NO\(_3^--\)N concentration in the groundwater was partly due to fertilization and nitrification in the upland soil at the crop-rotated paddy fields. Yonebayashi & Minami (2013) reported that the high NO\(_3^--\)N concentrations in groundwater near north-east parts were affected by the nitrogen load originated from domestic wastewater. Among the three types of waters, the concentrations of NH\(_4^+\)-N, PO\(_4^{3-}\)-P, T-P, and TOC were the lowest in the groundwater, and the highest in the paddy water, suggesting that their mineralization and adsorption on soil particles in the process of soil water movement from the soil surface to groundwater. NO\(_2^-\)N was not detected in most of the groundwater samples and all paddy waters.

The observed concentrations for many elements were evaluated by comparison with the environmental standard. Table 1 shows environmental standards related to the groundwater quality. These standards were limited to measured water quality elements in this study (Ministry of the Environment 1948, 1997; Ministry of Health Labor & Welfare 2002). Compared with the standard value for NO\(_3^--\)N (the sum of the concentrations of NO\(_3^--\)N and NO\(_2^-\)N is under 10 mg/L), there is no danger of groundwater pollution.

The range of the mean concentration of dissolved components in the groundwater is 1,000–10,000 μg/L for Na, 100–1,000 μg/L for Sr, 10–100 μg/L for B, NO\(_2^-\)N and Zn, 1–10 μg/L for Al, Ba, Cu, Fe, Li, and Mn, and less than 1 μg/L for As, Cd, Cr, Mo, Ni, Pb, Sb, and Se. Cd and Fe, however, were not detected in almost of groundwater samples. Only one sample of groundwater exceeds the standard of Mn. It was concluded that groundwater pollution did not occur in the fan.

Table 1 | Environmental standards

<table>
<thead>
<tr>
<th>Element</th>
<th>Standard (mg/L)</th>
<th>Remark</th>
<th>Element</th>
<th>Standard (mg/L)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1</td>
<td>A</td>
<td>Cu</td>
<td>1</td>
<td>B</td>
</tr>
<tr>
<td>Se</td>
<td>0.01</td>
<td>A and B</td>
<td>Cl</td>
<td>200</td>
<td>B</td>
</tr>
<tr>
<td>Pb</td>
<td>0.01</td>
<td>A and B</td>
<td>Na</td>
<td>200</td>
<td>B</td>
</tr>
<tr>
<td>NO(_3^--)N and NO(_2^-)N</td>
<td>10</td>
<td>A and B</td>
<td>Mn</td>
<td>0.05</td>
<td>B</td>
</tr>
<tr>
<td>Cd</td>
<td>0.003</td>
<td>A</td>
<td>Sb</td>
<td>0.015</td>
<td>C</td>
</tr>
<tr>
<td>Cd</td>
<td>0.01</td>
<td>B</td>
<td>Ni</td>
<td>0.01</td>
<td>B</td>
</tr>
<tr>
<td>As</td>
<td>0.01</td>
<td>B</td>
<td>NO(_2^-)N</td>
<td>0.05</td>
<td>B</td>
</tr>
<tr>
<td>Cr</td>
<td>0.05</td>
<td>B</td>
<td>Ba</td>
<td>0.7</td>
<td>B</td>
</tr>
<tr>
<td>Zn</td>
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<td>B</td>
<td>Mo</td>
<td>0.07</td>
<td>B</td>
</tr>
<tr>
<td>Al</td>
<td>0.2</td>
<td>B</td>
<td>Li</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>Fe</td>
<td>0.2</td>
<td>B</td>
<td>Sr</td>
<td>10</td>
<td>C</td>
</tr>
</tbody>
</table>

A: standard relating to water pollution (Ministry of the Environment 1997); B: standard relating to tap water (Ministry of Health Labour & Welfare 2002); C: standard relating to hot spring (Ministry of the Environment 1948).
The spatial distributions of some ions and elements in the shallow groundwater are shown in Figure 5. Some remarkable spatial distribution properties of dissolved ions and multiple elements in shallow groundwater samples were confirmed. The spatial distribution properties can be categorized into three groups. Group 1 is composed of TN, Cl, Mg, δD, and δ18O, whose values in the groundwater increased with distance from the river. This increase is due to the decreasing dilution of recharging river water with low values. Group 2 is composed of NO3-N, Ca, and Sr, whose concentrations in the groundwater are low near the Tedori River and the north-eastern part of the fan, and are high around the center of the fan where the paddy field distributes. The elevation of NO3-N is ascribed to the input of fertilizer, whereas those of Ca and Sr are likely due to their selective dissolution from the soil and rock in the fan by acids, which are generated from the decomposition of fertilizer and paddy rice (Nakano et al. 2008). If excluding the maximum point (north edge and middle of the Sai River) of NO3-N in the shallow groundwater, then the distribution of the shallow groundwater is similar to that of TN. This result confirmed that most of the nitrogen species in the

Figure 5 | Spatial distributions of water quality components in the shallow groundwater. Note: black and gray circles represent the river water and paddy water, respectively. The size of circle shows the concentration of water quality component. (Continued.)
groundwater was NO$_3$-N. Group 3 is composed of elements of B, Sb, and Mo, whose concentrations decrease with the distance from the Tedori River. Other elements excluding these three groups showed a sporadic distribution. From Groups 1 and 2, inflow from the Tedori River to groundwater caused a significant decrease in the concentrations in shallow groundwater through a dilution effect. The dilution effect on the shallow groundwater was confirmed.
from the Tedori River to the center of the fan. From Group 2, the infiltration water from the paddy fields also affected the spatial distributions of groundwater qualities.

**CONCLUSIONS**

This study applied a multiple water quality analysis to investigation of the actual water quality in groundwater under an alluvial fan where irrigated paddy fields are the dominant land use. Spatial distribution of some ions and elements were examined by simultaneous sampling for groundwater, river water, spring water, and paddy water.

Observed results revealed that the pollution of groundwater qualities did not occur. Some water quality indicators (including TN, Cl, Mg, and isotopes in water) exhibit similar spatial distributions with low concentrations along the Tedori River and their concentrations increasing with distance from the river. This indicates that water infiltrated from the Tedori River to the shallow groundwater, which dilutes the groundwater. Several substances (NO3-N, Ca, and Sr) occurred in low concentrations near both rivers and high concentration around the center of the fan where the paddy field area ratios were relatively large, indicating that the paddy water affects groundwater qualities. It is important to conserve water qualities of Tedori River for groundwater quality conservation in this alluvial fan.

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**REFERENCES**


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