Surface discharge of heavy metals from low farmland

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Abstract Runoff heavy metals from farmland were examined using the field data for the summer of 2005. The observation farmland is located on lowland where the irrigation water was contaminated with the drained water from the upstream farmlands. The area of the farmland is 11.2 ha, of which 6.0 ha and 4.5 ha have been used for rice paddy fields and soybean cultivation, respectively. During the observation, heavy metal concentrations at the downstream end were usually found to be higher than those in the irrigation water. That is, the heavy metal concentrations increased due to the passage of the water through the farmland. This increase in the heavy metal concentrations is not equal to the discharge of the heavy metal because the evaporation on the surface of the paddy field and the absorption by plants makes the surface water volume small. The discharged load from the farmland generally indicates the gross surface load from the farmland. When the effects of circulation irrigation on the heavy metal concentrations are estimated, the discharged load from the farmland should be calculated as the net surface load. When the runoff heavy metals from the circulation irrigation farmland are estimated, it is important to consider the inflowing heavy metals with irrigation water. All the heavy metal types observed in this study were discharged from the farmland. The net surface loads of Cr, Fe, Cd, and Pb were 3.71 mg m⁻² day⁻¹, 14.9 mg m⁻² day⁻¹, 0.26 mg m⁻² day⁻¹, and 3.3 mg m⁻² day⁻¹, respectively.

Keywords Heavy metal; low farmland; surface discharge

Introduction

The management of nutrient load balance in farmland is a very important environmental issue for all downstream watersheds such as coastal zones and closed water bodies. Nitrogen, a nutrient, is discharged from farmland because of fertilization. Fertilized ammonium nitrogen is easily nitrified to nitrite or nitrate under an aerobic environment. However, it is widely known that nitrate and nitrite nitrogen are removed by denitrification from the ponded water in rice paddy fields. Recycling of water in irrigation and drainage systems is one method of enhancing such ability, and reduces the concentration of dissolved nitrogen.

On the other hand, recycling of water involves the danger of increasing the heavy metal concentrations. Some heavy metals are necessary to the maintenance of life, but some heavy metals form toxic chemical compounds and affect the ecosystem (Arizono, 1999). Excess heavy metal loads, one of the causes of the increase in heavy metal concentrations, become a serious problem. Some of the heavy metals in the natural environment are in a very low concentration. It is difficult to analyze these with high accuracy. Recently, improvements in the analysis methods have facilitated the realization of highly accurate analysis of trace elements (Yoshinaga, 1999).

Heavy metal concentration in various situations has been reported. For instance, Mori et al. (1987) reported the amount of heavy metals discharged from domestic wastewater, Ebise and Miki (2001) reported the runoff of heavy metals in a river, and Assadian et al. (2003) reported heavy metal distribution in the upper Rio Grande basin. This analysis method has also been adapted to the studies of agriculture. McBride and Graemem (2001)
reported heavy metal concentrations in fertilizer and manure, and Lee (2005) reported heavy metal concentrations in the surface soil in a paddy field and in the soil solution extracted from the paddy soil. To our knowledge, runoff heavy metals from farmlands have hardly been examined in detail thus far. Not a few papers which estimated heavy metals concentration in the soil have been published. However, the heavy metal concentration in the runoff water from farmland has been estimated in very few papers.

In this study, runoff heavy metals from farmland were examined using the field data for the summer of 2005. The gross runoff loads and the net surface discharge loads of heavy metals from the farmland are calculated and discussed.

**Methods**

**Observation farmland**

The observation farmland is located on the lowland on the coast of Ariake bay in the Kyushu Island of Japan (33°8'N, 130°26'E) where irrigation water was contaminated with the drained water from upstream farmlands (see Figure 1). A strip of farmland with a drainage canal flowing in a T shape was selected for the observation. Since the water flow was simple, it was comparatively easy to calculate the water and nutrient mass balances in the farmland.

The drainage canal has gates at the east and north ends (upstream ends). The west end (downstream end) of the canal has no gate between the canal and the creek. The gate on the east end of the drainage canal is always closed, but slight leakage from the creek to the canal was sometimes observed when the water level in the creek was extremely high. Usually, the gate on the north end of the canal is partially opened, and inflows from the north canal were observed. A small village is located to the north of the observation field. Thus, the domestic wastewater flows into the canal through the north gate.

The area of the farmland is 11.2 ha (170 m × 660 m), of which 6.7 ha and 4.5 ha are used for rice paddy fields and soybean cultivation, respectively (see Figure 1).
Observation period and interval

Water flows were observed and water samples were collected from August 24 to September 1 (8 days) in 2005. The sample water was collected from 4 points on the creek and drainage canal every 4 hours. The collected samples were kept in cool storage and carried to the laboratory as soon as possible. Heavy metal concentrations were analyzed in the laboratory.

The average atmospheric temperatures during the observation period at Kurume City and Omuta City (see Figure 1) were 27.1°C and 26.8°C, respectively. These are neighboring cities of Yanagawa City and have the Automated Meteorological Data Acquisition System (AMeDAS). The average water temperature in the observation drainage canal was 28.0°C. The total rainfall was 9 mm, and the maximum rainfall intensity was 2 mm hr⁻¹. There was no rain which influenced the drainage from farmlands during the observation period.

Water flow observation

The water flow volume at the point located at the upstream end (Sta. A-1) was observed by a triangular measurement weir. At the other points (Sta. A-3 and A-5), it was calculated from the areas and water flow velocities. The water flow velocities and water levels were measured by the 2-dimensional electromagnetic flow meter (Kenek Corp., VP 2000) and the automatic water level meter with a pressure gauge (STS Sensor Technik Sirnach AG, MC1100W), respectively.

An influent water flow from the north gate sometimes became very large, and this caused a backward flow from the Sta. A-4 to the east drainage canal. This implies that the water balance tends to be unstable in such a situation. Therefore, the data were selected from the entire data based on two viewpoints as follows: 1) no backward flow from the Sta. A-4 toward Sta. A-1 should be observed and 2) the water level throughout the drainage canal must be almost the same as compared to that 4 hours before. In this study, to ignore the effects of rainfall, a period with no or a little rain was selected.

Heavy metal concentration analysis

The concentrations of chromium, iron, cadmium, and lead were analyzed by inductively coupled plasma mass spectrometry (ICP-MS; Parkin Elmer, Inc., ELAN DRC-II) after decomposition. The total heavy metal concentration was estimated from the target isotope concentration and content in nature. The target isotope of each heavy metal element (⁵²Cr, ⁶⁷Fe, ¹¹²Cd, and ²⁰⁷Pb) was selected to secure optimum sensitivities. Decomposition was carried out by using a microwave oven (Milestone, ETHOS TC) employing the Easy Control Program No.B0031 (Milestone General).

Estimation of water and mass balances

Water balance was calculated from the difference between the inflow and outflow water volume of the drainage canal to calculate the gross runoff load.

\[
[\text{Water balance}] = [\text{Water flow at Sta. A-5}] - [\text{Water flow at Sta. A-3}] - [\text{Water flow at Sta. A-1}]
\]

The discharged load from the farmland generally indicates the gross surface load (runoff load) from the farmland. The runoff load is calculated from the difference of the heavy metal transportation between the upstream and downstream ends of the drainage canal.

\[
[\text{Gross runoff load}] = [\text{Load at Sta. A-5}] - [\text{Load at Sta. A-3}] - [\text{Load at Sta. A-1}]
\]

The net surface discharge load is defined with the following formula:

\[
[\text{Net surface discharge load}] = [\text{Gross runoff load}] + [\text{Percolation load}] - [\text{Irrigation load}]
\]
In this study, the measurements of percolation water were not carried out. Therefore, it was assumed that the percolation water volume was constant (3 mm day$^{-1}$) and the concentration in the percolation water was the same as in the irrigation water. The irrigation load was calculated according to the following formula:

\[
\text{Irrigation load} = \text{[Irrigation water volume]} \times \text{[Concentration at Sta. C-1]}
\]

\[
\text{Irrigation water volume} = \text{[Water flow at Sta. A-5]} - \text{[Water flow at Sta. A-3]}
\]

\[
\text{Water flow at Sta. A-1} + \text{[Percolation water volume]} + \text{[Evaporation water volume]}
\]

The evaporation water volume was calculated with the Makkink equation. The regional parameters of the Makkink equation were quoted from the paper by Nagai (1993).

**Results and discussion**

**Heavy metal concentration**

*Figure 2* shows the observed results of Cr and Fe. The averages of the analyzed heavy metal concentration in the creek and the drainage canal were Cr: $3.1 \pm 1.8 \mu g L^{-1}$, Fe: $0.66 \pm 0.39 mg L^{-1}$, Cd: $0.03 \pm 0.02 \mu g L^{-1}$, and Pb: $1.1 \pm 0.6 \mu g L^{-1}$. Table 1 lists the reported heavy metal concentrations. Heavy metal concentrations in the drainage canal were lower than those concentrations in the rivers and wastewater. Cr and Fe concentrations were higher than those of the effluent from the wastewater treatment plant.

Heavy metal concentrations at A-3 seemed to be slightly higher than those at A-1, especially when the water flow at A-3 was high. These might be caused by the drain from a small farming village that lies to the north of the observed farmland. This village has no domestic sewage systems, and the inflow from the north gate, excluding night soil, indicates a possibility of wastewater contamination (e.g. drainage from kitchens, baths, and laundry facilities).
The heavy metal concentrations in the downstream end were usually higher than those in the irrigation water during the observation (see Figure 2). In other words, the heavy metal concentrations increased due to the passage of the water through the farmland. Evaporation and absorption by plants change the water volume in the farmland block. The changes in the water volume have an effect on the heavy metal concentration. Thus, an increase in the heavy metal concentration is not equal to the discharge of the heavy metal. Therefore, it is important to evaluate the discharge of the heavy metal.

Comparison between gross runoff load and net surface discharge load

The gross runoff loads of heavy metals are calculated based on the result of water balances. The gross runoff loads of Cr, Fe, Cd, and Pb were 690 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), 39.3 \( \text{mg m}^{-2} \text{ day}^{-1} \), 0.97 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), and 27.8 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), respectively (see Table 2). All the heavy metal types observed in this study were discharged from the farmland.

When the effects of the recycling irrigation on heavy metal concentrations are estimated, it is important to consider the inflowing heavy metals with the irrigation water, and the discharged load from the farmland should not be calculated as a gross runoff load but a net surface load. The net surface loads of Cr, Fe, Cd, and Pb were calculated as 371 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), 14.9 \( \text{mg m}^{-2} \text{ day}^{-1} \), 0.26 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), and 3.3 \( \mu \text{g m}^{-2} \text{ day}^{-1} \), respectively (see Table 2). These results indicate that the farmland is a source of heavy metal loads.

This implies that the repetitive usage of the creek water involves some risk of making the heavy metal concentration very high. When the recycled water is used in the irrigation and drainage systems, the consideration of heavy metal concentrations may become essential for irrigation water management.

In this study, high percentages of the net surface load compared with runoff load were observed. These percentages of Cr, Fe, Cd, and Pb were around 50, 40, 30, and 10%, respectively. This result suggests that the high surface discharge loads had discharged in the observation period. The collected data indicate that a rice field that is very close to the observation farmland was managed to maintain a high water level in the ponding water, and some of the rice paddy fields were in the intermittent irrigation period during the observation period. Therefore, the high surface discharge loads were possibly drained with the intermittent drainage. Furthermore, each kind of matter has a different discharge

### Table 1
Reported heavy metal concentration (average value)

<table>
<thead>
<tr>
<th></th>
<th>Cr*</th>
<th>Fe**</th>
<th>Cd*</th>
<th>Pb*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>River (R. Yodo, Japan; flowing in the urban area)</td>
<td>–</td>
<td>0.02</td>
<td>1.8</td>
<td>4.8</td>
<td>Ebise and Miki (2001)</td>
</tr>
<tr>
<td>–</td>
<td>0.09</td>
<td>1.6</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>0.03</td>
<td>0.7</td>
<td>6.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>2.3</td>
<td>0.05</td>
<td>1.8</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Soil solution extracted from paddy soil</td>
<td>–</td>
<td>14.1</td>
<td>50</td>
<td>370</td>
<td>Lee (2005)</td>
</tr>
<tr>
<td>Tap water</td>
<td>0.8</td>
<td>0.06</td>
<td>0.1</td>
<td>6.5</td>
<td>Mori et al. (1987)</td>
</tr>
<tr>
<td>Domestic wastewater</td>
<td>3.5</td>
<td>1.19</td>
<td>0.5</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>Effluent from wastewater treatment plant</td>
<td>1.1</td>
<td>0.18</td>
<td>0.3</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>

Unit for *: \( \mu \text{g m}^{-2} \text{ day}^{-1} \); unit for **: \( \text{mg m}^{-2} \text{ day}^{-1} \)

### Table 2
Comparison between net surface discharge load and gross runoff load

<table>
<thead>
<tr>
<th></th>
<th>Cr*</th>
<th>Fe**</th>
<th>Cd*</th>
<th>Pb*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net surface discharge load</td>
<td>371</td>
<td>14.9</td>
<td>0.26</td>
<td>3.3</td>
</tr>
<tr>
<td>Runoff load</td>
<td>690</td>
<td>39.3</td>
<td>0.97</td>
<td>27.8</td>
</tr>
</tbody>
</table>

Unit for *: \( \mu \text{g m}^{-2} \text{ day}^{-1} \); unit for **: \( \text{mg m}^{-2} \text{ day}^{-1} \)
process, and the process is influenced by the environmental conditions such as oxidation-reduction potential (ORP), pH, concentrations of other chemical compounds, and so on.

These loads were discharged from the farmland where mixed cultivation of rice and soybean was carried out. In fact, there are almost no surface discharges from soybean fields during fine weather. Therefore, it is considered that these loads depended on the surface discharges from rice paddy fields. Further observation would be required to understand the entire discharge from farmlands, including the discharge for rainy days.

Conclusions
The surface discharge loads of observed heavy metals had discharged in the observation period. It is considered that farmlands tend to be the source of heavy metal loads. Therefore, when recycled water is used in irrigation and drainage systems, the consideration of heavy metal concentrations becomes essential for irrigation water management.

To the best of our knowledge, few studies have estimated the runoff heavy metals from the low farmlands located in the lowlands around Ariake Bay. Rapid investigation is required to determine the yield coefficient of the farmlands located in lowlands. Furthermore, the chemical forms of the heavy metals in nature are very important for the discussion of their toxicities. In the future, further examination of their bases is required.

Acknowledgements
This study was partly founded by Research and Development Program for Resolving Critical Issue, Commissioned by the Ministry of Education, Culture, Sports, Science and Technology of Japan, “Rehabilitation of Ariake Bay and Demonstration of Rehabilitation Technologies”.

We would like to thank the staff of Mitsuhashi Land Improvement District and Yanagawa City Office. We also thank the Kyushu Regional Agricultural Administration Office of the Ministry of Agriculture, Forestry and Fisheries for their advice and assistance with data collection.

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