Long-term trends in water quality in an under-populated watershed and influence of precipitation

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ABSTRACT
An investigation of the water quality in an under-populated watershed was conducted over a 15-year period in which data was collected at weekly intervals. The purposes of this study were to analyze the long-term trends in water quality and to evaluate the relationship between the water quality and precipitation. Concentrations of total phosphorus (T–P), chemical oxygen demand (COD), and suspended solids (SS) reached remarkably high values under heavy precipitation conditions, and these concentrations increased exponentially with the amount of precipitation. Over the course of this study, the population, number of factories, animals (cow and pig), and area of agricultural land exhibited clearly decreasing trends, while steady progress in domestic wastewater treatment was realized. However, no clear decrease in the parameters of water quality was observed, and some nitrogen, phosphorus, and COD concentrations increased even though no significant change in precipitation occurred. A possible hypothesis explaining this lack of a clear decrease in water quality is that specific pollutant outflows from forests and agricultural lands may have increased in recent years. This is because poorly managed forests and agricultural lands in the under-populated watershed have adversely affected the water quality of the rivers.

Keywords: long-term trend, precipitation, under-populated watershed, water quality.

INTRODUCTION
In recent years, the deterioration of water quality in closed water areas such as lakes, reservoirs, and ponds has been regarded as one of the most serious problems threatening the aquatic environment. In Japan, the water quality in many such areas has not shown clear improvement in the last 30 years and the chemical oxygen demand (COD) in the water meets environmental standards in only 40–50% of cases (Ministry of Environment of Japan, 2008). Two of those lakes that fail to meet COD standards are Lake Shinji (area = 79.2 km², mean depth = 4.5 m) and Lake Nakaumi (86.8 km², 5.4 m) in the eastern part of Shimane Prefecture, which are representative of brackish lakes in Japan. In these lakes, the water quality has never met the expected environmental standards for total nitrogen (T–N), total phosphorus (T–P), and COD, which are 0.4 mg L⁻¹, 0.03 mg L⁻¹, and 3 mg L⁻¹, respectively (Shimane Prefecture, 2008a). In addition, blooms of blue-green algae and red tide are occasionally observed. On the other hand, the pollutant fluxes from terrestrial areas, which can have a marked effect on the aquatic environment in lakes, can differ greatly from year to year, because the water quality and pollutant load in rivers is strongly influenced by the uncontrollable hydrological condition of precipitation. Therefore, it is necessary to investigate long-term trends regarding water quality and pollutant load in rivers.
The migration of a large number of people from rural to urban areas is a trend observed not only in Japan but throughout the world. In rural areas, this migration can cause depopulation, aging of the local population, and a consequent increase in poorly managed forests and agricultural lands. Therefore, increased migration may adversely affect the water quality in the aquatic environment. However, sufficient data on water quality and pollutant loads in under-populated watersheds have not been collected, nor has an effective evaluation been conducted.

We have been investigating the water quality in an under-populated watershed since August 1991 by measuring the levels of nitrogen, phosphorus, organic matter, and suspended solids (SS) at weekly intervals. For this investigation, the watershed of the Hii River was chosen as the study site since it is the largest river flowing into Lake Shinji and the population in the watershed had been decreasing. The purposes of this study were to analyze the long-term trends in the water quality of an under-populated watershed for the period from 1992 to 2006 and to evaluate the relationship between the water quality and precipitation.

This study focuses on the amount of precipitation as a hydrological factor affecting the aquatic environment, because strong relationships have been reported between the amounts of precipitation and the pollutant loads in several watersheds (Kunimatsu and Sudo, 1997; Sugimoto et al., 2008). Moreover, a greater amount of reliable data is available on precipitation than on runoff. For example, in the governmental monitoring system in Japan, the amount of precipitation is monitored at about 1300 stations using the Automated Meteorological Data Acquisition System (AMeDAS), and these data are made available to the public almost immediately (e.g., Japan Meteorological Agency, 2006). On the other hand, the amount of runoff is monitored at only about 370 stations and the data are made available a few years after collection (e.g., Japan River Association, 2008). Therefore, determining the relationship between water quality and precipitation would be useful for evaluating the aquatic environment even if the runoff data could not be obtained.

MATERIALS AND METHODS
Study site

In this study, the Hii River located in the eastern part of Shimane Prefecture was chosen as the study site (Fig. 1). Water in the Hii River was sampled every week at points H1 (midstream) and H2 (downstream). The areas of the watershed at points H1 and H2 are 451 and 911 km², respectively, and their land-use characteristics are similar with a large amount of forested land. Specifically, the land use at the H1 watershed was 83.5% forest, 8.7% agricultural, 0.8% residential, and 7.0% for other purposes while the land use at the H2 watershed was 80.8% forest, 10.0% agricultural, 1.4% residential, and 7.8% for other purposes. Table 1 shows the changes in several point sources and various domestic wastewater treatments performed from 1990 to 2005, which were estimated from statistical data and information obtained from Shimane Prefectural Government (e.g., Shimane Prefecture, 2000; Shimane Prefecture, 2006; Shimane Prefecture, 2008b). Since accurate statistical data are not available for the number of hens, these data are not listed in this table. The population of H1 and H2 watersheds decreased by 10.3% and
7.8%, respectively, between 1990 and 2005. In this period, the number of factories and animals also decreased. In 2000, the population densities of H1 and H2 watersheds were calculated to be 46 and 78 inhabitants km\(^{-2}\), respectively, whereas the average population density in Japan was 342 inhabitants km\(^{-2}\). Accordingly, the studied
watershed is characterized as an under-populated watershed with a pronounced depopulation trend. On the other hand, domestic wastewater treatment clearly increased. For example, the percentage of domestic wastewater treatment (sewerage, small sewerage in rural areas, and domestic septic tanks) in the H2 watershed increased from 18.9% in 1990 to 64.5% in 2005. Therefore, pollutant emissions originating from domestic wastewater were expected to decrease during this period.

Water quality analysis
The methods for analyzing the water quality of the collected samples were in accordance with Japanese Industrial Standard (JIS) K 0102 (Namiki, 1993): T–N was measured by UV absorption spectroscopy after alkaline potassium peroxodisulfate decomposition; ammonium nitrogen (NH4–N) was measured by the indophenol blue method; nitrate nitrogen (NO3–N) was measured by ion chromatography using a Shimadzu HIC–6A system; T–P was measured by the ascorbic acid reduction molybdenum blue method after potassium peroxodisulfate decomposition; phosphate phosphorus (PO4–P) was measured by the ascorbic acid reduction molybdenum blue method; COD was measured by the potassium permanganate method; and SS was measured by the glass fiber filter paper method (pore size = 0.45 μm; Advanted GS25). Among the measured parameters of water quality, NO3–N and COD have been analyzed since March 1993 and the qualitative analyses for NO3–N, NH4–N, and PO4–P were conducted after filtration.

Collection of precipitation data
The daily precipitation data was obtained from the AMeDAS as stated above. The arithmetic averages of the data from four monitoring points located in or near the Hii River watershed were used as the precipitation data (Fig. 1). The altitude of these points varied from 20 to 369 m.

RESULTS
Changes in concentration
Figure 2 shows the changes in the concentrations of nitrogen, phosphorus, COD, and SS at point H2. In addition, the average values and standard deviations of the concentrations during the entire study period are listed in Table 2. Overall, the levels of the T–N, T–P, COD, and SS concentrations increased under heavy precipitation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H1</th>
<th>H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-N (mg L⁻¹)</td>
<td>0.577 ± 0.338</td>
<td>0.636 ± 0.329</td>
</tr>
<tr>
<td>NH4-N (mg L⁻¹)</td>
<td>0.038 ± 0.028</td>
<td>0.032 ± 0.028</td>
</tr>
<tr>
<td>NO3-N (mg L⁻¹)</td>
<td>0.349 ± 0.135</td>
<td>0.378 ± 0.154</td>
</tr>
<tr>
<td>T-P (mg L⁻¹)</td>
<td>0.035 ± 0.053</td>
<td>0.043 ± 0.055</td>
</tr>
<tr>
<td>PO4-P (mg L⁻¹)</td>
<td>0.011 ± 0.006</td>
<td>0.013 ± 0.006</td>
</tr>
<tr>
<td>COD (mg L⁻¹)</td>
<td>1.6 ± 2.1</td>
<td>1.7 ± 1.4</td>
</tr>
<tr>
<td>SS (mg L⁻¹)</td>
<td>7.7 ± 23.1</td>
<td>9.6 ± 22.6</td>
</tr>
</tbody>
</table>
conditions. However, all heavy precipitations do not have the concentration peaks, because the concentrations are weekly data while the precipitations are the daily averages. Among these peaks, many of the T–P, COD, and SS concentrations are considerably higher than the corresponding averages (T–P = 0.043 mg L\(^{-1}\), COD = 1.7 mg L\(^{-1}\), SS = 9.6 mg L\(^{-1}\)), and many peaks of T–N concentration are relatively higher than the corresponding average (0.636 mg L\(^{-1}\)). On the other hand, the concentrations of inorganic substances (NH\(_4\)-N, NO\(_3\)-N, PO\(_4\)-P) fluctuated within a very narrow range. Cross-correlation analysis revealed high correlations between SS and T–N (R\(^2\) = 0.816; p < 0.01 at point H1, R\(^2\) = 0.720; p < 0.01 at point H2), SS and T–P (R\(^2\) = 0.859; p <
0.01 at point H1, \( R^2 = 0.724; p < 0.01 \) at point H2), and SS and COD (\( R^2 = 0.867; p < 0.01 \) at point H1, \( R^2 = 0.644; p < 0.01 \) at point H2). Thus, the concentrations of T–N, T–P, and COD were strongly related to the particulate matter.

As shown in Table 2, most of the average concentrations at point H2 were slightly higher than those at H1, likely reflecting the differing land use at the sites. In particular, the H2 watershed had slightly larger areas of agricultural and residential land. For nitrogen, the average concentrations of NO\(_3\)–N were approximately 60% of the T–N concentrations, whereas the NH\(_4\)–N concentrations were considerably smaller. The standard deviations of T–P, COD (except at point H2), and SS were higher than the corresponding average values, as a result of the high peak concentrations described above.

**Annual average concentrations**

*Figure 3* shows the annual average concentrations and the annual amounts of precipitation. In this figure, the results of linear regression analyses are also shown. The mean value of the annual amounts of precipitation for the entire study period was 1811 mm. It should be noted that the annual amount of precipitation in 1993 (2304 mm) was the largest during the study period and the summer of that year is generally remembered as a “cool and rainy summer” by many Japanese. As a result of the many rainy days with accompanying low temperature and lack of sunshine, serious damage to rice crops occurred throughout Japan. In addition, the annual amounts of precipitation were relatively high in 1997 (2186 mm), 2001 (2003 mm), and 2003 (2045 mm). On the
other hand, the annual amount of precipitation in 1994 was the lowest (1339 mm) during the study period, and the drought in this year caused a serious water shortage nationwide. In the remaining years, the annual amounts of precipitation were in the range of approximately 1600 to 1900 mm. Linear regression analysis did not reveal any particular long-term trend.

Many plots of concentration at point H2 are slightly higher than those at point H1 with the exception of the NH4–N concentration. High T–N, T–P, COD, and SS concentrations were observed in 1993 due to the unusually large amount of precipitation, as stated above. In addition, the T–P, COD and SS concentrations in 2002 at point H2 were also high, but the annual amount of precipitation in this year (1596 mm) was not large. This is because the annual averages in 2002 were strongly affected by a single datum collected on July 2nd (T–P = 0.766 mg L\(^{-1}\), COD = 18.4 mg L\(^{-1}\), and SS = 380 mg L\(^{-1}\); amount of precipitation on the sampling day = 35 mm). In linear regression analyses, clearly increasing trends were observed for T–N and NO3–N concentrations, but no clear trend was observed for the remaining concentrations.

**Relationship between concentration and precipitation**

Since the annual average concentrations of T–N, T–P, COD and SS were partially reflected in the annual amount of precipitation as stated above, a correlation analysis was conducted between them. **Figure 4** shows the relationship between these variables.

![Figure 4](image)

**Fig. 4** - Relationship between annual precipitation and annual average concentration at point H1.

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Fig. 5 - Relationship between the concentration of each sample and the combined amount of precipitation on the sampling day and the preceding day.
at point H1. All the concentrations tended to increase with annual precipitation (p > 0.05), and similar results were obtained at point H2. However, the higher levels of T–P, COD, and SS concentrations in 2002 were strongly affected by the single datum as stated above, and some levels in 1997, 2001, and 2003 were somewhat low (Fig. 3) despite the large amounts of annual precipitation (2186 mm in 1997; 2003 mm in 2001; 2045 mm in 2003). Therefore, the effects of precipitation on water quality are difficult to determine if annual variables are used.

From this, a correlation analysis was conducted between the T–N, T–P, COD, and SS concentrations measured on each sampling day and the combined amount of precipitation on the sampling day and the preceding day. Regression lines of linear equations were calculated but had low R² values, for example, 0.292 for T–N, 0.385 for T–P, 0.338 for COD, and 0.283 for SS at point H1. On the other hand, exponential equations showed better agreement and statistically significant relations (p < 0.01) were found (Fig. 5). In addition, the values of the exponents of T–P (0.0211 for point H1; 0.0232 for point H2), COD (0.0165 for point H1; 0.0184 for point H2), and SS (0.0249 for point H1; 0.0295 for point H2) were higher than those of T–N (0.00978 for point H1; 0.0112 for point H2). Therefore, the concentrations increased exponentially with the amount of precipitation, and this increase was more pronounced for T–P, COD, and SS than for T–N, supporting the fact that their levels were considerably higher under heavy precipitation conditions (Fig. 2). This regression (Fig. 5) is a meaningful relationship for the long-term trend analysis of the water quality stated below. This is because if a clear trend of precipitation is recognized, long-term trends in water quality will be affected by the long-term trend of precipitation.

Comparison of five-year data sets
Long-term trends in water quality were also analyzed by comparing three data sets, each containing data collected over five years with box plots drawn as shown in Fig. 6. Since the concentrations of T–N, T–P, COD, and SS of each sampling datum were significantly affected by precipitation (Fig. 5), the amounts of precipitation for all rainy day, and for the sampling day and the preceding day were analyzed in the same manner. These data sets did not follow a normal distribution and the variance within the data sets was not equivalent; thus, the nonparametric analysis of Steal-Dwass test after Kruskal-Wallis U-test was performed. No significant difference was observed within the data sets of precipitation. However, significant differences (p < 0.05) were found within the T–N data sets at points H1 and H2, T–P data sets at point H2, and COD data sets at point H2. From these results, it was concluded that the T–N (at points H1 and H2), T–P (at point H2), and COD (at point H2) concentrations exhibited increasing trends, even though the precipitation data sets did not show any apparent trend. Furthermore, the remaining concentrations did not have any increasing or decreasing trends.

DISCUSSION
In previous studies analyzing long-term trends regarding water quality and/or pollutant load in rivers, it has been reported that the progress of wastewater treatments effectively reduced the nitrogen and phosphorus concentrations in rivers (Lehmann and Rode, 2001; Parr and Mason, 2003; Pastres et al., 2004), while the expansion of agricultural practices caused the levels of these components to increase (Macdonald et al., 1995;
Fig. 6 - Box plot of three data sets of precipitation and the concentrations of various water quality parameters. Solid line in the box is the median, lower and upper broken lines represent the 25th and 75th percentiles, and lower and upper ends of solid lines represent the 5th and 95th percentiles, respectively. Different letters near the boxes indicate significant difference (p < 0.05). Closed circles are averages. In some boxes of SS concentration, there are not lines corresponding to the 5th and 25th percentile, since more than half of all data were not larger than the median.
Stow et al., 2001; Zhou et al., 2000). In the Hii River watershed, there were clear decreases in population, number of factories, and animals, while there was steady progress in terms of domestic wastewater treatments (Table 1). In addition, the area of cultivated lands in the Hii River watershed in 2005 was 15% less than that in 1990, and there was no drastic change in agricultural practices (e.g., Shimane prefecture, 2008b; Shimane Prefecture, 2000). Consequently, a trend of decreasing water quality was expected, but a clearly decreasing trend was not found. On the contrary, some concentrations increased significantly, as shown in Fig. 3 and Fig. 6, despite a lack of significant change in precipitation.

A possible hypothesis explaining this phenomenon is that specific pollutant outflows from forests and agricultural lands may have increased in recent years. Because poorly managed forests and agricultural lands have adversely affected the water quality in the following way.

In forests (covering approximately two-thirds of the land in Japan), delayed thinning of conifer plantations (covering approximately 40% of all forests) due to depopulation and aging of the local population is recognized as one of the most serious problems not only for forest management but also for the aquatic environment (e.g., Ministry of Agriculture, Forestry and Fisheries, 2008a). This is because delayed thinning leads to a closed canopy that prevents sunlight from reaching the forest floor and undergrowth disappears. Then, the nutrient-rich soil surface would be subject to erosion. Moreover, the forests in which thinning is thought to be necessary have been estimated to comprise more than half of the conifer plantations all over Japan (Ministry of Public Management, Home Affairs, Posts and Telecommunications, 2003). In the Hii River watershed, conifer plantations account for 43% of the forested land and 63% of these conifer plantations were expected to undergo thinning (Shimane prefecture, 2003). In a case study of this problem, it has been reported that delayed thinning of conifer plantations was responsible for increased amounts of pollutant runoff, as determined by comparing the pollutant loads from a watershed with delayed thinning and a reference watershed (Takeda and Kageyama, 2001; Takeda, 2002). Specifically, runoff loads of T–N, T–P, COD, and SS in the watershed with delayed thinning were respectively 1.7, 4.1, 1.9 and 2.2 times larger than the corresponding values of the reference watershed.

On the other hand for agricultural lands, the area of cultivated land in the Hii River watershed decreased as stated above. In addition, the area of “cultivation abandonment ground”, which is a statistical term used in the “Agricultural and Forestry Census” (Shimane Prefecture, 2005) and defined as lands on which there has been no record of cultivation in the preceding year and no cultivation plans for the following few years, increased by 12% between 1990 and 2005. In particular, this trend of cultivation abandonment has been recognized as a serious problem all over Japan (e.g., Ministry of Agriculture, Forestry and Fisheries, 2008b). In flat areas in downstream regions, the cultivation abandonment ground can be converted into residential or commercial areas, but in mountainous rural areas, most of this land is left unmanaged. Consequently, the nutrient-rich soil surface resulting from previous agricultural activity would be subject to erosion.

Among these nutrients, an increasing trend of phosphorus content in arable soil was
reported by a long-term nationwide surveillance (Obara and Nakai, 2004). Furthermore, the phosphorus content of much of the soil exceeded the required levels for cultivation. For example, it has been reported that the arable soils in 23–47% of vegetable fields and 54–78% of institutional fields contained excessive phosphorus. Therefore, it is a matter of concern that the high levels of nutrients in the soil of poorly managed agricultural land may increase the amount of pollutants in rivers, especially phosphorus.

In addition, it is also a concern that increased abandonment of paddy fields may adversely affect the aquatic environment. This is because some paddy fields can perform as pollutant sinks (Tabuchi and Hasegawa, 1995; Iwata et al., 1995) and paddy fields account for approximately 50% of the agricultural land in Japan. In addition, effective phosphorus purification has been observed in a paddy field watershed located in the downstream area of the Hii River (Takeda and Fukushima, 2004; Takeda and Fukushima, 2006). However, there is insufficient data to clearly indicate the relationship between poorly managed agricultural land and the increasing trend of pollutants in rivers, although some simulation results support this hypothesis (Masumoto et al., 2003; Sagehashi et al., 2008). Therefore, various methods for monitoring and analyzing this relationship are necessary.

CONCLUSIONS
In this study, long-term trends in water quality in an under-populated watershed were analyzed and the relationships between water quality and precipitation were evaluated. The data obtained in this 15-year investigation demonstrated that T–P, COD, and SS concentrations reached remarkably high values under heavy precipitation conditions and these concentrations increased exponentially with the amount of precipitation. In the study watershed, there were clear decreases in the local population, number of factories, animals, and area of agricultural land, while steady progress in domestic wastewater treatment was realized; thus, decreasing trends in water quality were expected. However, no clear decreasing trend was observed in the annual averages of concentrations, and T–N and NO$_3$–N concentrations had increasing trends. In a comparison of three data sets, increasing T–N, T–P, and COD concentrations were also observed, while the other concentrations and the amount of precipitation showed no clear increasing or decreasing trend. A possible hypothesis explaining this lack of a clear decreasing trend in the water quality is that specific pollutant outflows from forests and agricultural lands may have increased in recent years. This is because poorly managed forests and agricultural lands in the under-populated watershed have adversely affected the water quality of the rivers.

ACKNOWLEDGEMENTS
This study was partially supported by Shimane University Priority Research Project and a Grant-in-Aid for Scientific Research (#20380179) from the Japan Society for the Promotion of Science (JSPS).

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