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# Nutrients and Suspended Sediment Load Estimates for the Ishikari River Basin, Japan, Over a Decade

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## Synopsis

The load estimation process for nutrients (nitrogen and phosphorus) and suspended sediment (SS) is complicated because of retransformation bias, data censoring, and non-normality. To obtain reliable unbiased estimates, the regression model Load Estimator (LOADEST) was applied to estimate total nitrogen (TN), total phosphorus (TP) and SS loads at five sites in the Ishikari River Basin, Japan, from 2000 to 2010. Coefficients of determination ($R^2$) for the best-fit regression models for loads of TN, TP, and SS for the five sites ranged from 75.36 % to 92.37 %, suggesting the model for all three constituents successfully simulated the variability in constituent loads at all sites. Moreover, the estimated seasonal loads fluctuated widely during 2000 to 2010, with the greatest loads occurring in spring and the smallest loads occurring in winter. Accurately estimated loads are essential for effective water resources management efforts.

**Keywords:** nitrogen, phosphorus, suspended sediment, LOADEST, Ishikari River basin

## 1. Introduction

Surface water quality has important effects on aquatic ecosystems and human health. Nutrients (primarily nitrogen and phosphorus) are essential for plant and animal life, but in high concentrations they can cause lots of ecological problems including algal blooms, decreased dissolved oxygen concentrations, and increased fish mortality (Carpenter et al., 1998; Sprague and Lorenz, 2009). Suspended sediment (SS, soil and other particulate matter) is ubiquitous in aquatic ecosystems and contributes to bottom material composition, water-column turbidity, and chemical constituent transport. But excessive amounts of SS can degrade water quality and harm aquatic ecosystems through physical, biological, and chemical processes (Terrio, 2007). It is crucial to explore the temporal dynamics of nutrients and SS concentrations and loads in surface waters to effectively manage and protect water resources (Gruber and Galloway, 2008; Sprague and Lorenz, 2009).

Nutrients and SS concentrations and loads are generally estimated using models on the basis of infrequent and incomplete monitoring data (Armour et al., 2009; Duan et al., 2012; He et al., 2011; He et al., 2009; Luo et al., 2011). In addition, few estimates of nutrient loads reported in the literature present associated uncertainties (Kulasova et al., 2012). Observational uncertainty is critically important in defining and contributing to parametric uncertainty and errors in the conceptual models underpinning diffuse pollution research and management. Many countries have therefore developed monitoring programs and protocols such as the National Monitoring and Assessment Programme (NOVA) in Denmark (Conley et al., 2002; Kronvang et al., 2005), the Harmonised Monitoring Scheme (HMS) in Britain (Hurley et al., 1996; Morvan et al., 2008), and the National Water-Quality Assessment (NAWQA) in US (Gilliom et al., 1995; Rosen and Lapham, 2008), which enable a reliable quantification of nitrogen (N), phosphorus (P), and SS loadings and concentrations in the aquatic environment. Meanwhile, load estimating methods and models have improved substantially (Shrestha et al., 2008). In Japan, relevant efforts in water management have led to significant improvements in the estimation of water quality. For example, a nationwide data collection network (http://www1.river.go.jp/) called the National Land with

Water Information has been established to provide real-time water information including water quality, precipitation, and river discharge data. These monitoring systems are essential for evaluating and understanding the various hydrologic and biogeochemical processes governing water quality and nutrient cycling in watersheds and their ecological impacts. Because the load estimation process is complicated by retransformation bias (Ferguson, 1986; Webb et al., 1997), data censoring (Gilbert, 1987), and non-normality (Helsel and Hirsch, 1992; Shumway et al., 2002), only one fraction of the total nutrient load can usually be estimated in many modeling studies (Johnes, 2007). There is therefore an urgent need to improve estimation methods to compliment improving monitoring programs and resolve common shortcomings in estimation methods.

In this study, we introduce a methodology for the quantification of TN, TP, and SS loads in receiving waters associated with rivers. We describe a procedure for estimation of constituent loads in rivers which have been subject to only sparse measurements of flow and water quality constituents. The primary goal of this study was to estimate seasonal TN, TP, and SS loads using regression methods on the basis of instantaneous samples.

## 2. Materials and methods

### 2.1 Study area and data collection

The Ishikari River basin is located in central Hokkaido Island within the range of 43° N and 44° N, with total drainage area of 14,330 km$^2$ (see Fig.1). The Ishikari River originates from Mt. Ishikaridake (elev. 1967 m) in the Taisetsu Mountains of central Hokkaido, and then flows southward into the broad Ishikari Plain and finally into the Japan Sea. The length of the Ishikari River mainstream is 268 km and ranks third longest river in Japan. Major tributaries of the river include the Chūbetsu, Uryū, Sorachi, and Toyohira. The highest elevation in the Ishikari Plain is less than 50 m and the plain is bordered by a mountain range with peaks exceeding 1,000 m in elevation. At the Sapporo weather station (elev. 17 m), monthly air temperature in the warmest month (August) is 22.0 °C, and the coldest month (January) is -4.1 °C. Snow cover in Sapporo lasts for approximately four months from December to March. Average annual snowfall is 630cm, and the years deepest snow depth averages 101cm (normal value 1970-2000) (USUTANI and NAKATSUGAWA, 2006).

Five monitoring sites were chosen for analysis in this study (see Fig.1). Sites Yinou-oohashi, Yiwamizawao-ohashi, and Yishikarikakou-bashi are located in the upper, middle and lower reaches of the mainstem, respectively, while sites Akane-bashi and Umaoyi-bashi are located in the Uryū and Yūbari Tributaries, respectively. Samples of water quality (TN, TP, and SS) concentration and river discharge were collected at each site from 2000 to 2010 by the National Land with Water Information (http://www1.river.go.jp/) monitoring network. In general, water quality concentration and river discharge were measured and collected once a month at each site. Monthly samples were collected at sites Akane-bashi, Yinouo-ohashi, and Umaoyi-bashi, with a total number of 132 for each testing parameter at each site; 94 samples were collected for each testing parameter at Sites Yiwamizawao-ohashi and Yishikarikakou-bashi.

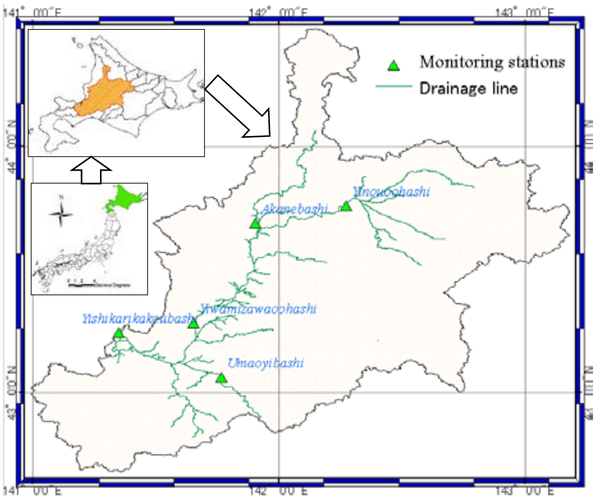


Fig.1 Study area, and monitoring stations for the Ishikari River basin

### 2.2 Methods

Stream-water SS or chemical constituent load ($\emptyset$) can be calculated using constituent concentration ($C$) and discharge ($Q$) integrated over time ($t$):

$$\emptyset = \int C(t)Q(t)dt \quad (1)$$

A continuous record of concentration and discharge is required to estimate loads using the integral in equation 1. Although discharge can be easily measured at a sufficiently high frequency, however, the expense of collecting and analyzing samples for water quality constituents means it is often difficult to obtain continuous data. Equation 1 can therefore be written as:

$$L_T = \Delta t \sum_{i=1}^{n} L_i \quad (2)$$

Where $L_T$ is an estimate of total load, $L_i$ is an estimate of instantaneous load, n is the munber of discrete points in time, and $\Delta t$ is the time interval represented by the instantaneous load.

In addition, the FORTRAN Load Estimator (LOADEST) uses time-series streamflow data and constituent concentrations to calibrate a regression model that describes constituent loads in terms of various functions of streamflow and time, enabling a direct calculation of equation 2 (Runkel et al., 2004). LOADEST performs calibration procedures and makes load estimates with four statistical estimation methods: Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), Linear Attribution Method (LAM), and Least Absolute

Deviation (LAD). AMLE and MLE are suitable when the model calibration errors (residuals) are normally distributed; AMLE is the more appropriate method of the two when the calibration data set contains censored data (that are reported as less than or greater than some threshold). LAM and LAD are useful when the residuals are not normally distributed. Because the input data in this study included censored data, and because the model calibration residuals were normally distributed within acceptable limits, the AMLE estimation method was selected in each site. The output regression model equations take the following general form (Runkel et al., 2004):

$$\ln(L_i) = a + b\ln Q + c\ln Q^2 + d\sin(2\pi dtime) + e\cos(2\pi dtime) + f\,dtime + g dtime^2 + \varepsilon \qquad (3)$$

Where ln is the natural logarithm; $L_i$ is the calculated load for sample $i$; $Q$ is stream discharge; $dtime$ is time, in decimal years from the beginning of the calibration period; $\varepsilon$ is error; and $a$, $b$, $c$, $d$, $e$, $f$, $g$ are the fitted parameters in the multiple regression model. Some of the regression equations in this study did not include all of the above terms, depending on the lowest Akaike Information Criterion (*AIC*) values (Sakamoto et al., 1986).

$$AIC = 2k - 2\ln(L) \qquad (4)$$

Where $k$ is the number of parameters in the statistical model, and $L$ is the maximized value of the likelihood function for the estimated model.

Combining the equations above, monthly and seasonal average TN, TP and SS loads were calculated. The seasons were considered in the following way: winter (December, January, February); spring (March, April, May); summer (June, July, August); autumn (September, October, November).

## 3. Results and discussions

### 3.1 Regression evaluation

Coefficients of determination ($R^2$) for the best-fit regression models for loads of TN, TP, and SS for the five studied sites (Table 1) performed well (site Akane-bashi was the best), ranging from 75.36 % to 92.37 %, which indicated that, with few exceptions, the models for all three constituents successfully simulated the variability in constituent loads at all sites.

Meanwhile, according the calibrated data at each site, different models were selected on basis of the lowest *AIC* and then coefficients were calculated using the AMLE (Table 1). For TN estimation at site Akane-bashi, the lowest of *AIC* was 0.640 and the coefficients $a$, $b$, $c$, $d$, $e$, $f$, and $g$ were 7.3230, 1.0553, -0.0261, -0.2401, -0.0679, 0.0034, and 0.0063; while at site Umaoyi-bashi, the lowest of *AIC* was 1.128 and the coefficients only had $a$ (6.1154) and $b$ (0.9993).

### 3.2 Estimated loads

For the sake of brevity, only monthly average TN, TP, and SS loads at site Akane-bashi are displayed in time-series graphs (Fig. 2). As a measure of error associated with monthly average load estimates, the upper and lower 95-percent confidence intervals are also presented in Fig. 2, showing in most cases the measured loads track very closely with model estimations with little systematic underestimation or overestimation in load, which are in accordance with the result of Table 1. At site Akane-bashi, monthly average TN, TP, and SS loads ranged from 40.06 to 24 198.00 kg/day, 7.03 to 3 025 kg/day, and 662.00 to 5802 000.00 kg/day, respectively. At all sites, monthly average TN, TP, and SS loads displayed seasonal fluctuations in both loads and in discharge from 2000 to 2010, even though the dates of peak discharge were not the same every year.

Table 1 Regression coefficients, coefficients of determination ($R^2$) and AIC for load models used to estimate TN, TP, and SS at five sites in the Ishikari River basin, Japan, 2000-2010.

| Site name | Regression Coefficient | | | | | | | $R^2$ (%) | *AIC* |
|---|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | *c* | *d* | *e* | *f* | *g* | | |
| TN | | | | | | | | | |
| Akane-bashi | 7.3230 | 1.0553 | -0.0261 | -0.2401 | -0.0679 | 0.0034 | 0.0063 | 92.37 | 0.640 |
| Yinou-oohashi | 8.9870 | 0.9728 | 0.1712 | -0.1830 | -0.1826 | | | 80.58 | 0.224 |
| Yiwamizawa-oohashi | 10.0929 | 0.9067 | 0.1399 | 0.1790 | | | | 90.95 | -0.468 |
| Yishikarikakou-bashi | 10.7065 | 0.8580 | -0.0884 | 0.1172 | 0.1679 | 0.01920 | | 83.01 | 0.002 |
| Umaoyi-bashi | 6.1154 | 0.9993 | | | | | | 88.08 | 1.128 |
| TP | | | | | | | | | |
| Akane-bashi | 4.6447 | 1.0492 | 0.0155 | -0.0423 | 0.5761 | -0.0382 | 0.0132 | 89.22 | 1.246 |
| Yinou-oohashi | 5.8819 | 1.0057 | 0.2986 | -0.1936 | 0.1403 | -0.0200 | | 73.56 | 1.125 |
| Yiwamizawa-oohashi | 7.2254 | 1.3063 | 0.1654 | 0.0961 | -0.2149 | | | 84.70 | 1.099 |
| Yishikarikakou-bashi | 7.8004 | 1.1607 | 0.1373 | 0.0418 | -0.1754 | | | 89.40 | 0.341 |
| Umaoyi-bashi | 3.2585 | 1.2014 | 0.0640 | 0.1210 | 0.3819 | -0.0505 | | 91.80 | 1.241 |
| SS | | | | | | | | | |
| Akane-bashi | 10.3793 | 1.5759 | 0.0522 | 0.0476 | 0.4572 | -0.0998 | 0.0230 | 87.39 | 2.105 |
| Yinou-oohashi | 11.4478 | 1.4868 | 0.6994 | -0.1106 | 0.1899 | -0.0588 | | 76.14 | 1.747 |
| Yiwamizawa-oohashi | 13.0451 | 1.9803 | 0.3337 | -0.0919 | -0.3573 | -0.0408 | | 85.35 | 1.868 |
| Yishikarikakou-bashi | 12.9587 | 2.1178 | 0.3605 | -0.2020 | -0.4147 | -0.0528 | | 86.07 | 1.909 |
| Umaoyi-bashi | 9.5146 | 1.4798 | 0.1353 | 0.2914 | 0.4047 | -0.1122 | | 83.68 | 2.447 |

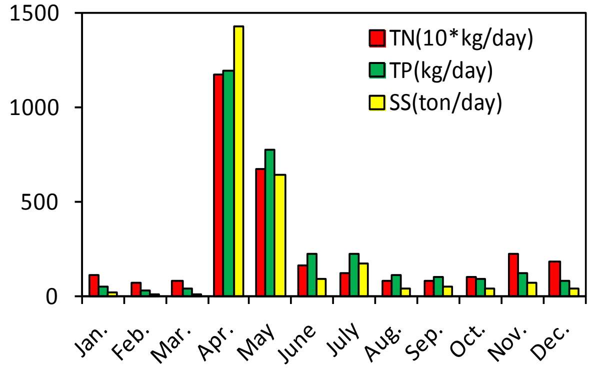


Fig.3 Estimated average loads of TN, TP, and SS, by month, at site Akane-bashi, 2000 to 2010.

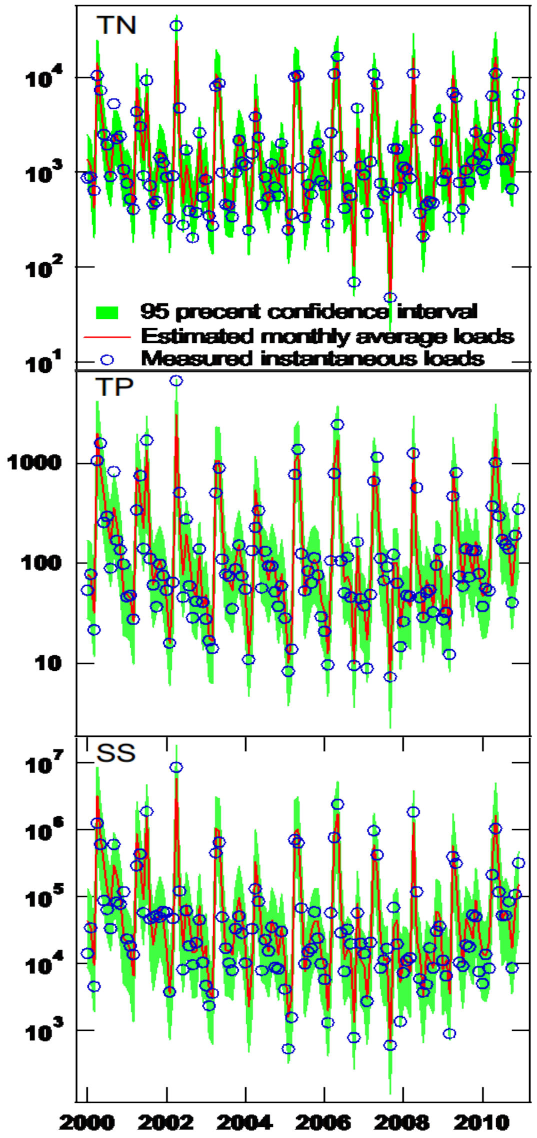


Fig.2 Estimated monthly average and measured loads (kg/day) of TN, TP, and SS at site Akane-bashi, 2000 to 2010

Figure 3 shows the estimated average loads of TN, TP, and SS by month at site Akane-bashi, 2000 to 2010, calculated by averaging the monthly averages for each month of the year (for example, the average of all January monthly averages, all February monthly averages, and so on). As can be seen from Fig. 3, the estimated average loads of TN, TP, and SS in April had the largest loads, the values of which were 11 720.0 kg/day, 1 191.00 kg/day and 1 429.09 ton/day, respectively; while January, February and March had relatively low loads. The results of other sites were similar to these.

Estimated seasonal loads of TN, TP, and SS at five sites were highly variable in 2000 and 2010 in the Ishikari River and its tributaries, with the greatest loads occurring in the spring and the smallest loads occurring in the winter (Table 2), reflecting fluctuations in discharge as a result of the combined effects of seasonal runoff patterns, the exact timing of which vary from year to year. At site Yishikarikakou-bashi, TN load decreased from 68 536 kg/day in spring to 36 064 kg/day in winter, TP load decreased from 7 098 to 1 439 kg/day, and SS decreased from 5803 000 to 212 497 kg/day. Seasonal alteration was consistent with monthly alteration (Fig. 3).

Whatever the season, site Yishikarikakou-bashi had the largest loads of TN, TP, and SS, far better than at other sites, the seasonal mean of which were 46 702 kg/day, 3 560 kg/day and 1 991 033 kg/day (Table 3).

Table 2 Estimated seasonal average loads (kg/day) in five sites in Ishikari River basin, from 2000 to 2010

| Site name | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| | TN | | | |
| Akanebashi | 6424 | 1207 | 1361 | 1176 |
| Yinouoohashi | 15639 | 8166 | 6582 | 6590 |
| Yiwamizawaoohashi | 41427 | 15816 | 20072 | 16719 |
| Yishikarikakoubashi | 68536 | 39480 | 42242 | 36064 |
| Umaoyibashi | 2361 | 1213 | 920 | 947 |
| | TP | | | |
| Akane-bashi | 669.06 | 181.89 | 102.88 | 51.24 |
| Yinouoohashi | 993 | 528 | 285.44 | 240.06 |
| Yiwamizawaoohashi | 5022 | 1345 | 1120 | 618.9 |
| Yishikarikakoubashi | 7098 | 3233 | 2407 | 1439 |
| Umaoyibashi | 302.97 | 162.81 | 72.7 | 50.71 |
| | SS | | | |
| Akane-bashi | 692088 | 97510 | 51964 | 21484 |
| Yinou-oohashi | 656252 | 197399 | 84867 | 60617 |
| Yiwamizawa-oohashi | 4633677 | 643348 | 481725 | 170036 |
| Yishikarikakou-bashi | 5.80E+06 | 1154298 | 705433 | 212479 |
| Umaoyi-bashi | 518835 | 273043 | 88395 | 49256 |

Table 3 Seasonal average loads (kg/day) in five sites in Ishikari River basin, from 2000 to 2010

| Site name | TN | TP | SS |
|---|---|---|---|
| Akanebashi | 2542.00 | 251.27 | 215761.00 |
| Yinouoohashi | 9244.00 | 511.59 | 249784.00 |
| Yiwamizawaoohashi | 23627.00 | 2043.00 | 1501764.00 |
| Yishikarikakoubashi | 46702.00 | 3560.00 | 1991033.00 |
| Umaoyibashi | 1360.00 | 147.30 | 232382.00 |

**(4) Discussions**

Based on the lowest of *AIC* of different models, the best models were chosen to estimate constituents at each site(Table 1), which can better simulate changes of concentrations and loads. For example, d, and e can directly show seasonal variation; that is, the bigger of the absolute value of d, and e, the larger of seasonal changes (Runkel et al., 2004). Meanwhile, calibrate data was used to calculate the coefficients using the AMLE method, which can eliminate the influence of censored data as much as possible. Data censoring that means less than the laboratory detection limit is common in measuring the constituent concentration, which specified by using a less-than sign (<) as the first character in this study. The performance of models was measured using $R^2$, showing good results.

Site Yishikarikakou-bashi had the highest loads of TN, TP, and SS, both in monthly and seasonal loads (Fig. 4, Table 2), because this site is located in the lower reaches of the Ishikari River and has the highest average discharge, which is the primary driver of delivery of all the constituents to the coastal waters (Fig. 4).

The estimated loads at all sites were greatest in spring, while lowest in winter. The Ishikari River basin is located in the northern part of Japan in central Hokkaido and therefore experiences large seasonal discharges associated with spring snowmelt. Floods in the Ishikari River Basin tend to occur in April and May, possibly explaining why the estimated loads were greatest in spring.

## 4. Conclusions

We estimate monthly and seasonal average River Basin, Japan, from 2000 to 2010, using the LOADEST regression model. Some important and interesting conclusions can be summarized as follows:

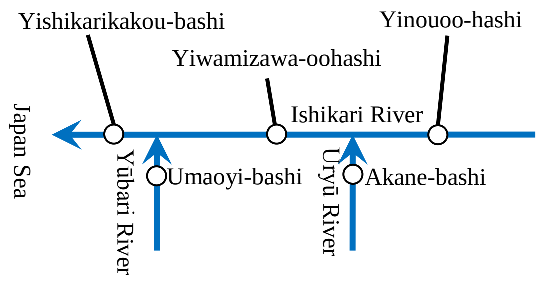


**Fig.4** Schematic diagram of the Ishikari River basin and five studied sites.

(1) Best-fit ($R^2$) regression models for loads of TN, TP, and SS for the five studied sites ranged from 75.36 % to 92.37 %, suggesting that the model for all three constituents successfully simulated the variability in constituent loads at all sites. Using the AMLE method, the influence of the data censoring was eliminated as much as possible.

(2) The estimated average loads of TN, TP, and SS by month were highly variable at five sites in the Ishikari River basin, between 2000 and 2010. For example, at site Akane-bashi, April had the largest loads, the values of which were 11720.0 kg/day, 1191.00 kg/day and 1429.09 ton/day, respectively; while January, February and March had relatively low loads.

(3) The estimated seasonal loads of TN, TP, and SS at five sites were highly variable in 2000 and 2010 in the Ishikari River and its tributaries, with the greatest loads occurring in the spring and the smallest loads occurring in the winter, reflecting fluctuations in discharge as a result of the combined effects of seasonal runoff patterns, the exact timing of which vary from year to year.

(4) Site Yishikarikakou-bashi is located in the lower reaches of the Ishikari River and has the highest average discharge, meaning the primary driver of delivery of all the constituents to the coastal waters. It therefore had the highest loads of TN, TP, and SS, both in monthly and seasonal loads.

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