Analyzing the bias in dry weather spot flow rates to periodical mean flow rates in mountain streams: toward determining water pollution loads and optimizing water sampling strategies

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Abstract:

Low frequency (once a month) but long-term (ca. 6 years) sampling including snow-melt periods in a mountainous stream, the Okura River (Sendai, Japan), revealed that loadings of 5 parameters (COD, TN, TP, TOC and D-SiO₂) could be expressed exponentially using discharge (Q), while the coefficients for the 5 loadings were all about 1. Here, mathematically, the periodically averaged Q leads to approximation of that of load (L). We analyzed the bias of the spot Q to that of the periodical (30, 14 and 8 days) means. The results ensured the utilization of the spot Q instead of the periodical mean Q for estimating L because of the high correlation factors (0.872, 0.914 and 0.923 on 30-, 14-, 8-day mean Q analyses, respectively) and suggested the validity of the usage of the observed regression slopes of 1.06, 1.22, and 1.22 over 30, 14, 8 days for quantitative correction of L because the fact that the slopes are larger than 1 indicate that the usage of the spot Q instead of the mean Q leads to the overestimation of L. Both changing correlation factors and the regression slopes realized small improvements via shortening the periods from 14 to 8 days. The protocol proposed here is quite original and is applicable to designing sampling strategies at target sites based on quantification of the limitations and/or reliability of L estimations.

KEYWORDS spot flow rate; periodical mean flow rate; snow-melt period; L-Q equation; Okura River; sampling strategy

INTRODUCTION

Evaluation of discharge loads (L) for non-point contamination sources has been receiving increasing attention (e.g. Tien et al., 2020). That paper used a loading (L) – discharge (Q) curve approach, in this study, we use the term, “L-Q relationship” or “L-Q equations”.

Generally, the evaluation of discharge loads (L) for non-point contamination sources requires both flow rate (Q) measurements and sampling at appropriate time intervals. Flow rates are commonly determined via automatic monitoring, however in some cases manual measurement method such as a float method for challenging environments (e.g. hilly streams) as shown in Harada and Ohno (2017) and Harada and Watanabe (2019), but are instead commonly determined via automatic monitoring. Thus, obtaining L via concentration measurements of nutrients and organic materials (C) is far more difficult than obtaining Q. Obtaining C depends on water sampling and follow-up chemical analyses in a laboratory. The authors’ primary interest is to devise a way to effectively detect variations in the runoff load (L) of nutrients and organic matter by multiplying Q and C (Harada et al., 2014; Tanno and Harada, 2017).

In our target rivers for analyzing the L-Q relationships there are mountainous streams that regulate base flow of the catchment comprising the downstream areas. Generally, the flowrate in mountainous streams show larger variations. High frequency monitoring is desirable but not always possible. Thus, developing sampling plans with expected bias and/or representativeness of the spot (instantaneous) Q and C (and the resulting L) in the study area that can be determined in advance is highly desirable. Based on the expected bias, we can assess the accuracy and precision of the estimates of L and may be able to improve the monitoring strategy. To our knowledge, no prior work in this area (attempting to quantify the bias of spot Q based on before and after flow conditions) has been conducted, with the exception of the authors’ own preliminary analyses (Harada et al., 2020a) which examined the representativeness of 41 spot Q against 30 day mean Q. It would be fair to say that the idea and the protocol of the analyses shown in our preliminary study was crude but quite original, however, we only showed that i) fair correlation between the parameters was obtained and ii) the 30 days mean Q could be underestimated if we use spot Q instead of the 30 days mean Q. The results did not suggest any valid usage of spot Q for the estimation of L.

In this study, we re-focus the relationship of spot Q and periodical mean Q based on monthly based observation on fair weather days from the Okura River, a mountain stream running into the Okura Dam. In the Okura River, automatically measured continuous flow rates were available. By using the recorded flow rate at the time of sampling, it was
possible to analyze the bias of the observed spot (instantaneous) flow rate in estimating the mean flow rates for 8-day, 14-day and 30-day periods.

The new idea shown in the present study, to analyze the expected bias between spot and periodical mean flow rates in the Okura River, is practical and effective for discussing water resources management in river systems. Aspects of this discussion include 1) the river runs through a large city (Sendai city, the biggest city in Tohoku region in Miyagi prefecture in the northern part of Japan), 2) the river catchment is located in a region experiencing cold winters and 3) the river is a mountainous stream. These three aspects are important for discussing the role of the river in terms of the wider basin, the importance of the characteristic phenomena in the river and the representativeness of the river. First, the discharge from the Okura Dam flows into the Hirosi River which run through Sendai city, thus the Okura River plays an important role in the management of water resources in the region; knowing the flow regimes (the variations in $Q$ and resulting water quality features (the variations in $C$ and $L$) is therefore important. Here, we propose that our novel methodology for analyzing the flow regimes and water quality of a river becomes a standard technique in terms of the analysis for water resources management plan, including in other important hydrological systems. Next, when we pay special attention on the fact that Okura River catchment is located in a cold winter region, the methodology accounting for the effects of snow covering and melting on flow regimes and the water quality features becomes applicable to other river catchments located in cold areas. Finally, with the forestry area in Japan exceeding 70% of the land surface, the Okura River, as a mountainous forest stream, shows common features of a large number of rivers that transport materials through forests in the country. The specific flow rates varied from 0 to 0.202 m$^3$/s/km$^2$, in the general range for natural forested areas in Tohoku (e.g. Haneda, 1998) and thus the Okura River is suitable as a representative study site for the region.

Here, as to $Q$ and $C$, in terms of their natural behavior, both are time dependent, mainly reflecting variations in climatological conditions. Moreover, $Q$ affects $C$ via dilution, etc., thus, $C$-$Q$ relationships can not be neglected. However, our focus is on assuming $L$, especially $L$ on fair-weather days, and thus we pay attention to $L$ rather than $C$-$Q$ relationships, since, empirically, we can determine firm $L$-$Q$ relationships from runoff loads at the sampling point (e.g. Yokota et al., 2013; Sugawara et al., 2017 and references cited therein). Knowing $Q$ essentially leads to a clarification of $L$.

Separately, we have reported preliminary analyses of $L$ and $Q$ relationship using 64 sets of spot $Q$ and five $L$ (i.e. Chemical Oxygen Demand (COD), Total Nitrogen (TN), Total Phosphorus (TP), Total Organic Carbon (TOC) and Dissolved Silicate (D-SiO$_2$)) via nonlinear fits (Table I) (Tanno and Harada, 2017). The five $L$ were expressed exponentially using $Q$ with coefficients for all 5 loads of about 1 (varied from 0.89 to 1.09) (Table I). Thus, mathematically, inputs of periodically averaged $Q$ approximate that of $L$. Via analyses of periodically averaged $Q$ approximate, we could show that the sensitivity related to changing the coefficient slightly around 1 was small (data not shown).

In the present study, we focus on analyses of the bias and representativeness of the spot (instantaneous) $Q$. The spot $Q$ values used in the study were obtained on fair days at the sampling site. Compared to sampling on rainy days, sampling in dry weather is easier, is less dangerous and requires less labor. The samples were taken monthly during dry weather for approximately six years (April 2011 to December 2016). In all, 64 sets of nutrients and organic matter concentrations were collected, along with the spot, instantaneous flow rates, which varied from 0 to 18 m$^3$/s. The histogram of the spot flow rates closely resembled that of all hourly flow rates (approximately 50,000 data) during the monitoring period (Tanno and Harada, 2017), suggesting that our monitoring succeeded in capturing the fair-weather flow regime at the site.

Automatically measured continuous flow rates are available at the site. Thus, by referring to the recorded flow rates at the time of sampling, it is possible to analyze the bias of the observed spot (instantaneous) flow rate versus the mean flow rate. We compared the bias of the spot values relative to the averaged flow rates over 8, 14 and 30 days (e.g. the average of measurements taken 15 days before and after the spot value was taken gives the one-month average) focusing on correlations, the slope of the regression line passing through the origin, and the range of data within the upper and lower bounds of the appropriate 95% confidence intervals.

Moreover, in the present study, we discuss the differences (if any) of the flow characteristics during the snow-melt period from the other periods. We determined the snow-melt period (from 2013–2015) using the oxygen-18 isotope ratio in nitrate ($\delta^{18}$O-NO$_3$), which is said to be higher during the snow-melt period because the value of $\delta^{18}$O-NO$_3$ in precipitation is significantly higher than that in soil water (Harada et al., 2017, 2020b).

Finally, we discuss other feasible $L$ assumption approaches using our own data which should come into consideration citing pre-reported references.

**METHODS**

Miyagi Prefecture provided hourly water level data and $H$-$Q$ curves (water height and flow quantity) at Jogi Station on the Okura River (Harada et al., 2017; Tanno and Harada, 2017) from 2011 to 2016. The site maps are shown in Harada et al. (2017). The water level data were converted to flow rates (m$^3$/s) and used for our analyses. Out of the lists of hourly flow rates recorded, the 64 spot flow rates were taken at the time as our monthly observations.
As noted, 64 sets of 30-, 14- and 8-day average flow rates were determined at Jogi station from April 2011 to December 2016 (excluding missing continuous or spot measurement data) from the 15, 7 and 4 days of continuous flow rate measurements collected at one-hour intervals before and after the selected spot flow rate. Correlation and regression analyses of the spot flow rate and the 30-, 14- and 8-day mean flow rates were performed and 95% confidence intervals were established.

The river water sampled from January to May 2013, from January to June 2014, and from January to October 2015 was immediately filtered using a GF75 glass fiber filter (ADVANTEC, 47 mm in diameter). The pore size of a GF75 filter is specified by the manufacturer as 0.3 micrometers; however, we separately examined the fraction of suspended solid in some samples at other sites and found that the size is quite similar to GF/B (Whatman, 47 mm in diameter, 1.0 micrometer pore size). A part of the filtrate was used to measure the NO$_3$-N concentration (HACH DR5000). The remainder was preserved frozen in a centrifugation vial. $^{18}$O$\text{-NO}_3$ was measured using the denitrifier method (Sigman et al., 2001) optimized in cooperation with the Interdisciplinary Centre for River Basin Environment, Yamanashi University (Harada et al., 2014, 2020b). The measurement accuracy at the center is ±0.3‰ relative to V-SMOW (Vienna Standard Mean Ocean Water) (Member of management committee of analytical system for water 170 isotopes at HyARC: the author of the literature2005 publication year of the literature; Harada et al., 2014, 2020b).

**RESULTS AND DISCUSSION**

Figures 1 to 3 show simple regression and correlation analyses of the spot flow rate (horizontal axis in the graph) and each of the three mean flow rates (vertical axis). In the graphs presented here, observation markers falling along the regression line indicate that the observed mean value and the mean value estimated from the spot value match. A marker above the line indicates that the actual mean value is greater than the estimated value; a marker below the line indicates that the mean value is less than the estimated value. The analyses produced statistically significant correlation factors ($R$ values) in all three cases, indicating that even the less-frequent sampling led to good approximations. The $R$ values were highest for the 8-day averages (0.923) and lowest for the 30-day averages (0.872), suggesting that the average flow regime was better represented using the shorter periods (the $R$ difference between the 8- and 14-day (0.914) cases was negligible). However, while the relatively large $R$ values might suggest that the spot flow rate provides good estimates of the mean flow rate, it should be noted that even for the 8-day averages, 13 points exceeded the upper bound of the 95% confidence interval and 5 points fell below the lower bound. The percentage of spot rates that plotted inside the 95% confidence interval was 71.8% (see also Figure 4).

Notably, the slopes of the regression lines passing through the origin were all larger than 1 (unity) (Figures 1–3), indicating that using the spot rate as a proxy for the mean flow rate tends to lead to an underestimation of the flow regime. A slope of 1 would mean that, on average, the spot rate matched the mean flow rate for the given averaging period. The slope was smallest for the 30-day average (1.06) and larger for the 8-day (1.22) and 14-day averages (1.22), indicating that the degree of difference from the mean was smallest for the longer averaging period (i.e. where the slope was closest to 1). The difference in slopes

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![Figure 1](image1.png)  
**Figure 1.** Spot vs 30-day mean flow rate with 95% confidence interval bounds (after Harada et al., 2020a)

![Figure 2](image2.png)  
**Figure 2.** Spot vs 14-day mean flow rate with 95% confidence interval bounds

![Figure 3](image3.png)  
**Figure 3.** Spot vs 8-day mean flow rate with 95% confidence interval bounds
between the 8- and 14-day cases was negligible. In general, the underestimation in evidence here appears reasonable since the spot samples were collected only on fair days. Importantly, the degree of underestimation bias can be estimated from the analyses. By realizing the magnitude of the bias, we should be able to quantitatively design a spot sampling strategy and to rigorously evaluate the results obtained.

As part of a sampling strategy, we need to analyze suitable sampling intervals. As the first step, we examined the effects of shortening the sampling intervals on the relationship of spot and mean flow rate. Our results suggested that a sampling interval of 8 days does not show significant improvement because both correlation factors and the regression slopes realized only small improvements via shortening the period from 14 days.

It could be said that the results of the present study are easy to appreciate because two important parameters showed monotonous trends: changes in the regression slopes and the correlation factors. At least, in the present study, we have clarified these features of the flow regime in the Okura River. However, when the proposed protocol is applied to some other rivers, it is possible that the two important parameters show different behavior. In this case, in the context of the present results, we have to pay attention on the trade-off effects between the representativeness of the spot flow rate versus mean flow rate and significance of the correlation factors (R values).

The variations in $\delta^{18}$O-NO$_3$ (Figure 5) indicate that the snow-melt periods were from February to May in 2013 and 2014 and from March to May in 2015, thus 11 sets of spot and 30-, 14- and 8-day average flow rates were defined as the ones belonging to the “snow-melt period”, compared to a total of 64 sets of flow rates. The plotted spot and mean flow rates for these snow-melt periods (overwritten by transparent star symbols) show similar patterns to the fair-weather points plotted in Figures 1–3, suggesting that the trends are fundamentally the same. Using the results shown in the Figure 3, we compared the proportion of points above the upper 95% confidence line, below the lower 95% line, and those inside the upper and lower 95% confidence lines for the entire period and snow-melt periods (Figure 4).

Because of a limited amount of data we did not conduct statistical analysis. However, we think the figure visually explains the fact that big differences in the 3 proportions did not emerge between the entire period and snow-melt periods.

The results shown here and the protocols in the present study are expected to provide: i) useful information on the frequency of regular river water sampling and motivate further studies leading to an ability to formulate optimal on-site sampling plans and ii) quantitative evidence on the limitations and/or reliability of assuming $L$ using periodical mean $Q$.

The motivations of the present study came from the necessity to examine methods utilizing data obtained via low frequency (once a month) monitoring over long periods (about 6 years) for $L$ estimation. Some previous studies (e.g. Inoue et al., 1998) have outlined daily sampling for exact measurement of $L$, however we think that further study contributing to reductions in the sampling frequency required is needed.

Here, we would like to explore previous studies conducted with similar motivations because the comparison between these approaches and those in the present study may clarify the novelty and/or advantages of our proposed protocol. Tada and Tanakamaru (2020) and Kawamura et al. (2020) showed an approach combining the usage of $L$-$Q$ equations with limited samplings (Importance resampling, therein). A similar approach to the present study can be found in the literature, including examining the utilization of pre-obtained data based on the usage of $L$-$Q$ equations. On the other hand, a deference can be seen whether or not additional procedure is needed. Tada and Tanakamaru (2020) requires “resampling” i.e. statistical extraction of some samples from the whole population based on statistical information while our approach requires quite simple comprehension of the data. Our proposed tech-

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Figure 4. Comparison of the proportion of points above the upper 95% confidence line, below the lower 95% a line and inside the upper and lower 95% confidence lines for the entire period and for snow-melt periods in Figure 3

Figure 5. $\delta^{18}$O-NO$_3$ in 2013, 2014 (after Harada et al., 2017) and 2015 (after Harada et al., 2020b)
nique offers a big advantage in terms of the utilization of data for academic and practical purposes.

On the other hand, our proposed methodology has not achieved utilization of the data in terms of “knowing the daily variations in $L$” but only for “knowing the periodical mean variations in $L$” using $L$-$Q$ equations. As such, for the former purpose, utilizing the method proposed in Tada and Tanakamaru (2020) and Kawamura et al. (2020) should be considered. The latter purpose is important for clarifying the expected bias when using the spot flowrate instead of periodical mean flowrate, which brings us to another novelty of our proposed technique, that is, the analyzed results lead to the examination of the optimal sampling strategy.

Again, for the purpose of “knowing the daily variations in $L$”, utilization of $L$-$Q$ equation is quite important together with analyses of the valid $Q$ range of proposed $L$-$Q$ equations. Yokota et al. (2013) examined the valid $Q$ ranges for the $L$-$Q$ equations via inter-comparisons of various estimation methods based on high frequent observation. Nihei et al. (2010) and Takioka et al. (2010) presented a protocol to complement the $L$-$Q$ equations for the case higher $Q$ data are not available. These approaches, absolutely, are helpful in utilizing our data for $L$ assumption based on $L$-$Q$ equations (in preparation).

Separately from the literature mentioned above, Ebise (1980) (and references therein) precisely explained the importance of hydrological approaches in terms of the $L$ assumption by focusing on the differences in the runoff mechanism between rainy and dry weather periods; this comparison should be incorporated into future work.

One point we want to underline is the importance of the $L$ in the stream during the fair-weather days, which is expected to supply baseflow nutrients and organic matter. In fact, when we focus on the supply of nutrients and organic matter to farmland nearby streams, the importance of baseflow $L$ is larger than high flowrate $L$ (which normally includes high turbidity water that is not supplied to farmland). Historically, assumption of total $L$ input from streams into enclosed water bodies downstream has received significant attention in terms of water quality control. The assumption knowing the downstream effects clearly requires estimation of the runoff $L$, thereby, runoff of all rainfall events including extraordinary extreme events should be considered.

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