Total loading curves applied to Lake Pyhäjärvi

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Abstract:

Total Dissolved and Suspended Solids are compiled in order to obtain total loading curves or load-discharge (L-Q) equations for the total solids concentration to a Finnish lake. It was before determined for Japanese rivers and compared with the world major rivers in literatures then extended to some Finnish rivers. Another empirical relationship containing reciprocal ionic fractions with TSS/TDS, ratio of suspended to dissolved matters is compared with Japanese data to think of spatial differences. The loading curves are used for the rivers flowing into Lake Pyhäjärvi, where sediment yields, average concentration, phosphorous adsorption and groundwater discharge at the lake floor are demonstrated.

1. Introduction

Loading estimation to a water body is the essential procedure by practical reasons. There are increasing needs to pursue total loading through rivers to a lake/sea during the past decades or even in the future. To estimate the total loading to Lake Pyhäjärvi, Total Dissolved Solids (TDS) or alternatively total dissolvable solids corresponding to Electric Conductivity (EC), Total Suspended Solids (TSS or just SS) and nutrients are investigated [1].

Murakami [2] collected and compiled silica and phosphate data (Colorimeter, DR-800, Hach) seven times bimonthly from more than 50 rivers flowing into Lake Biwa by round trips a year. In Fig.1, TSS/TDS is used as independent variable and TSS divided by SiO_2 or ionic species such as PO_4 as dependent variables, and the ratio was thought as the indicator of discharge in fields. It was known that a water sample is turbid when the discharge is high and vice versa.

Murata [3] extended Fig.1 to major river ions by using major ions (IA-200, TOADKK). It is true not only for SiO_2 and PO_4 but also major anions and cations. There is definite order in the reciprocal plot from region to region as shown in Fig.1. The fraction of TDS is locally fixed and stable in the downstream as SiO_2 and PO_4 are both 1 to 2 orders higher in Japan than in Finland. Temperature dependence of solubility is known and recent instruments can convert EC into TDS. The group of the highest fraction in Japanese data is: HCO_3^-(40), SiO_2(20), SO_4^{2-}(10), Ca^{2+}(10), Cl^-(10); <10%: Na^+(2), Mg^{2+}(2), K^+(2), NO_3^-(2); low <0.1%: NH_4^+, PO_4^{3-}, F^-, NO_2^-, Li^+

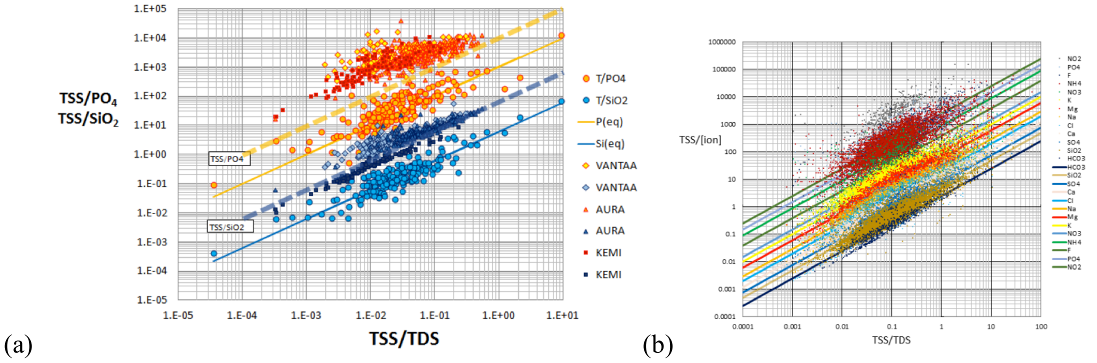

Fig. 1 (a) Reciprocal ionic fraction for silicate and phosphate in the Finnish rivers and rivers flowing into Lake Biwa; (b) This is valid for other ions considering the reference basis on y=x where TSS is replaced by TDS and showing TDS/ions.

The loading curves are shown in Fig.2 and $L_D = TDS \cdot Q$ in rivers were collected as follows: It is natural to expect a correlation between the total flux and discharge in *L-Q* curve, because the provided discharge *Q* is contained in both variables. The regime theory is of similar form to determine hydraulic quantities, width, depth and average velocity depending on the discharge *Q*.

Suzuki [4] analyzed EC and SS in the Ministry database and found *L-Q* equations for *TSS* in the 21 Class-A rivers flowing into Seto Inland Sea.

$$
\begin{aligned}
&L_S = L_{S1}\hat{Q}^{L_{S0}}, \quad L_D = L_{D1}\hat{Q}^{L_{D0}} \\
&L_S L_D^{-1} = L_{S1}L_{D1}^{-1}\hat{Q}^{L_{S0}-L_{D0}}, \quad TSS/TDS = k_1\hat{Q}^{k_0} \qquad (1) \\
&\hat{Q} = Q/Q_{ref}
\end{aligned}
$$

where Q_{ref} is taken 1 m^3s^{-1} so dimensionless discharge keeps the value as the dimensional one. Discharge is normalized and dimensional constraints are relaxed. Rating and loading curves would be simultaneously discussed.

$L_S = Q \cdot TSS$, $L_D = Q \cdot TDS$ are the total fluxes [kgs^{-1}];

L_{S1}, L_{D1} = coefficients denoting *TSS* and *TDS* at $Q = Q_{ref}$.

L_{S0}, L_{D0}=the exponents.

Yamada [5] analyzed water samples from the 21 rivers and summed up the major ions to obtain TDS. It was combined into curves depending on the hardness of water in Fig. 2. Three Kansai Rivers: Yodo, Yamato and Kino were frequently visited on various stage of discharge to get the exponent, which was found for the three rivers tested, L_{D0}: 0.75 to 0.80 and it was found to be up to 1.0 especially in continental rivers. This change corresponds to that of L_{S0} up to 1.75 to 2.0. Zheng [6] proved that the loading curves work well for sediment yields and phosphorous accumulation in Lake Poyang receiving the Gangjiang River, a major tributary of the Changjiang River. These are compared with the European rivers cited in Tockner *et al*. [7]. The inflows are Pyhäjoki and Yläneenjoki Rivers connected to the lake with the mouths. The only outflow occurs at the northern end with a narrow channel and more than 95% of the lake perimeter do not belong to these watersheds. There is the area of direct runoff to the lake without major streams and working as groundwater sources.

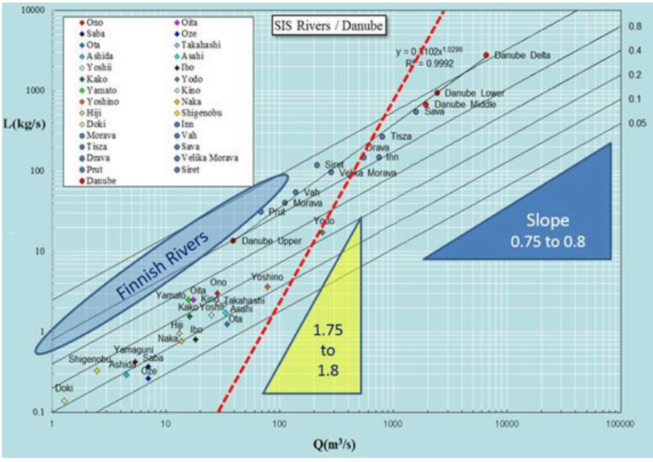

Fig. 2 Loading curves as L-Q equations for TDS

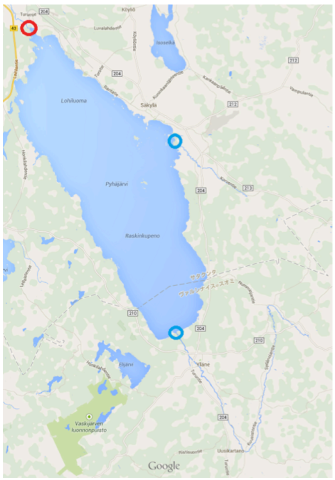

Fig. 3 Google map of Lake Pyhäjärvi
Blue circles: inflows; Red: outflow
The rest is the direct runoff region.

2. Methods

The loading curves for TSS, TDS and PO_4 are shown in Fig. 4 for the Pyhäjoki River and the Yläneenjoki River.

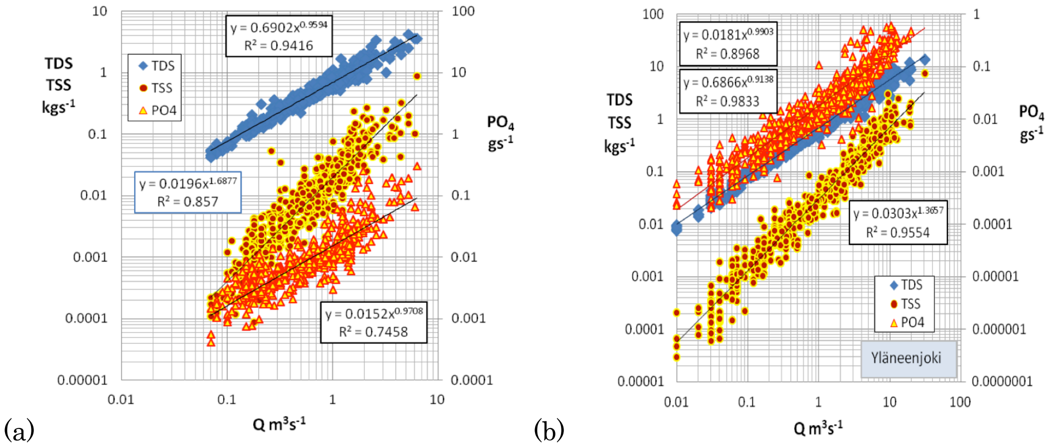

Fig. 4 The loading curves for the rivers:
(a) Pyhäjoki and (b) Yläneenjoki.

The way to calculate discharge is as follows:

The equations for the surface tank, $i = 1$,

$$\begin{aligned} dh_1/dt &= R - E - q_{11} - q_{12} - I_1 \\ q_{1j} &= \alpha_{1j}(h_1 - \zeta_{1j}), \;\; I_1 = \beta_1 h_1 \end{aligned} \quad (2)$$

Then subsurface tanks, $i > 1$

$$\begin{aligned} dh_i/dt &= I_{i-1} - q_i - I_i \\ q_i &= \alpha_i(h_i - \zeta_i), \;\; I_i = \beta_i h_i \end{aligned} \quad (3)$$

Table 1 Parameters of the tank model

		Ylaneen	Pyha
o		3	3
A	k m2	234.0	78.0
L	k m	120.0	54.0
i		0.010	0.010
Runoff Coef			
αsu	1/day	0.08	0.04
αsl		0.04	0.04
α2		0.03	0.02
α3		0.04	0.02
α4		0.001	0.001
Infiltration coef			
β1	1/day	0.02	0.03
β2		0.02	0.03
β3		0.003	0.002
outlet height			
ζ11	mm	15	8
ζ12		5	2
ζ2		20	2
ζ3		40	3
ζ4		60	2
constant / d		1	1
fraction_rain		0.4	0.4

where h is the depth, R=precipitation; E=evapotranspiration; q=the surface or subsurface runoff in lateral direction; I=infiltration to the lower reservoir; and α and β denotes runoff (lateral) and infiltration (vertical) coefficients respectively in Table 1. The lowest infiltration is not allowed, β_4=0 and only the latteral components α_4>0 are not drained to the rivers.

Evapotranspiration is calculated in the following paths: daily constant E_o; proportional to rain E_r; and snowmelt into water $-E_s$, which were tested 1 mm/day, 40% of rainfall on the previous day and manually.

The cascade runoff model in the above is an array of four-storied reservoirs in the soil column. It is so called “tank model” by Sugawara [9]. Discharge hydrographs are compared in Fig. 5 and measured discharges are used for calibration of the runoff model, which is selected here a four serial tank model for the watersheds.

3. Results

Some spring floods was not properly calculated in Fig.6 and negative evaporation was given for a snowmelt flood, which occur when the atmospheric temperature crosses the freezing point changing signs according to spring warming. This correction was made only when the observed discharge clearly exceeds the calculated one.

At higher discharges, the Yläneenjoki River conveys much water than the Pyhäjoki River and vice versa. It perhaps relates to the difference in the river courses: Pyhäjoki (P) is straight and Yläneenjoki (Y) shows sharp bending twice and minor floods disappear. Additionally, there would be groundwater effects in Pyhäjoki, where the runoff process going on with a delay to the surface runoff.

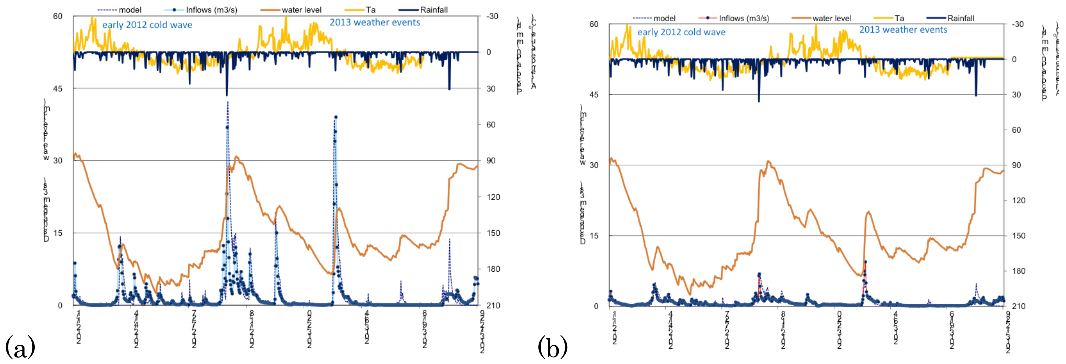

Fig. 5 Measured (marker) and observed (dotted line) hydrographs: (a) the Yläneenjoki River; (b) the Pyhäjoki River

4. Discussion

Fig.6 shows the runoff through the rivers in 2012 and 2013 was Q_A=165 million m^3, which is about 20% of the lake volume and the residence time is 10 years. Sediment yields in two rivers in the two years are found Q_s=10,200 tons and equivalent to 5,100 t/y, say 2,170 m^3/y, or a sedimentation rate of 14 mm/a. The concentration Q_s/Q_A is 62 gm^{-3} in total, or 77 gm^{-3} in Yläneenjoki and 32 gm^{-3} in Pyhäjoki River. The riverine PO_4 to sediment concentration Q_p/Q_s is 0.23 mg/kg (Y) and 0.48 mg/kg (P), and the lake average is 0.26 mg/kg, or Q_p=1,326 kg/a. Differences of outflow and inflows, precipitation and evapotranspiration are calculated and the latter is converted into discharge unit, then final residue is found as follows:

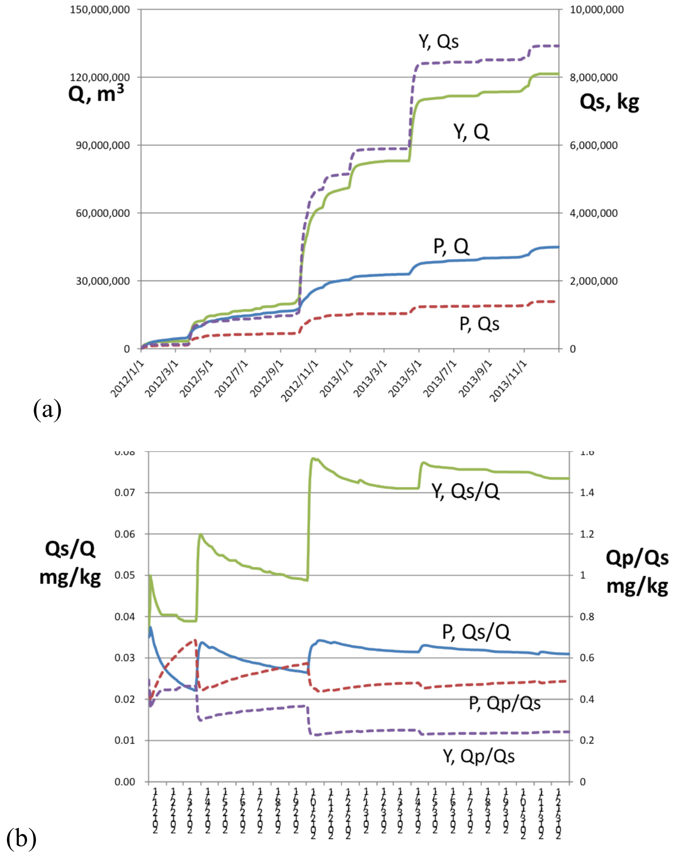

Fig. 6 (a) Annual discharge in volume and mass of the sediment yields in 2012-2013; and (b) cumulative average of sediment/nutrient entering into Lake Pyhäjärvi

$$
\begin{aligned}
q &= \sum_{day=1}^{730}(Q_O - Q_Y - Q_P) = 2{,}184 \quad m^3s^{-1}, \\
R_e &= \sum_{day=1}^{730}(R - E - E_S) = 725 \quad mmd^{-1}, \\
r_e &= R_e \times 155\cdot 10^3 / 86{,}400 = 1{,}301 \quad m^3s^{-1}, \\
q - r_e &= 2{,}184 - 1{,}301 = 883 \quad m^3s^{-1}
\end{aligned}
\qquad (4)
$$

To make the residue q-r_e vanish, increase in effective rainfall R_e by suppressing evaporation E or enlarge the lake area by 1.68 times, which means marginal watershed along the lake coast.

Table 2 Water Budget in Lake Pyhäjärvi (2012-2013)

River item	Yläneenjoki (m3/s)	Pyhäjoki (m3/s)	Release(m3/s)
	Qy	Qp	Qo
measured	1151	542	3877
calculated	1406	520	----
Σ (Qo-Qy-Qp)	2184.3		0.56
Re=Σ (R-E0-Es)	725.4		0.19
Re/Slake	1301.4		0.34
Residue	883.0		0.23

5. Conclusions

The loading curves or *L*-*Q* equations for TSS, TDS and PO_4 are determined for the two rivers inflowing to Lake Pyhäjärvi, South-West Finland. Those are extended to the Finnish rivers although the exponents (L_{D0}: 0.9-1.0; L_{S0}: 1.4-1.7) differs around 20% from Japanese rivers (L_{D0}: 0.75-0.80; L_{S0}: 1.75-1.80): The runoff tank model with four serial reservoirs of unit area in the watersheds is used and the *L*-*Q* equations are considered to estimate annual discharge Q_A=82.5 million m^3/a; sediment yields Q_S=5,100 t/a; and phosphorous loading Q_P=1,326 kg-PO_4/a.

In the runoff model, some floods are calculated by adding precipitation equivalent to daily snowmelt when the air temperature rises around the freezing point. A constant + delayed evapotranspiration is considered by the reason that the river inflows are only 60% of the outflow. The half of the rest 40% is explained by the direct effective precipitation (=*R*-*E*-*E*s) on the lake surface. There is still a residue of 20% in the outflow, which is to be included in the direct precipitation or it is temporally reduced by overestimating the evapotranspiration.

Acknowledgement

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References

[1] Finnish environmental administration, "the HERTTA water quality database", SYKE, 2013.

[2] M. Murakami, "Silica and phosphate transport in the watersheds surrounding Lake Biwa", Graduation Thesis, *Okayama University*, 2005.

[3] M. Murata, "Permeability, diffusivity and conductivity of unsaturated stratum with geo-chemical trans-spherical processes", Master's Thesis, *Okayama University*, 2008.

[4] S. Suzuki, "Sediment yields from rivers into the Seto Inland Sea", Master's Thesis, *Okayama University*, 2011.

[5] K. Yamada, "Longitudinal grade on total dissolvable solids in rivers", Master's Thesis, *Okayama University*, 2011.

[6] E. P. Zheng, "Hydrological processes of Lake Poyang, Jiangxi Province of China", Master's Thesis, *Okayama University*, 2014.

[7] K. Tockner, C. T. Robinson, U. Uehlinger, (Eds.) "Rivers of Europe", Academic Press, pp.59-112, 2009.

[8] A. J. Wiebe, "Quantifying the Groundwater Component within the Water Balance of a Large Lake in a Glaciated Watershed: Lake Pyhäjärvi, SW Finland", A thesis presented to the University of Waterloo in fulfillment of the thesis requirement for the degree of Master of Science in Earth Sciences, 2012.

[9] M Sugawara, "Automatic calibration of the tank model". *Hydrological Sciences Bulletin*, **24**, 3, pp. 375-388, 1979.