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TO: Bill Hashim
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SUBJECT: Lake Chelan TMDL for Total P

This memorandum presents the estimated allowable Total Maximum Daily Load (TMDL) for total phosphorus (TP) to Lake Chelan consistent with the Lake Chelan Water Quality Assessment conducted by Ecology (Patmont *et al.*, 1989). For the purposes of managing TP loads to Lake Chelan, the TMDL will apply to the total of external loads to the lower and upper basins and direct anthropogenic contributions from in-lake activities (e.g. fish net pens). The TMDL will be split into load allocations (LAs) for nonpoint sources and waste load allocations (WLAs) for point sources (e.g. net pens).

The Lake Chelan Water Quality Assessment was an extensive investigation of Lake Chelan, with the objectives of: 1) providing a baseline study of the lake; 2) evaluating the suitability of on-site wastewater disposal systems (septic tanks and drainfields) within the developing Lower Chelan Basin; and 3) estimating the principal sources and potential impacts of nutrients, bacteria, and other chemicals of concern to Lake Chelan.

The Lake Chelan Water Quality Assessment defined the primary management goal for Lake Chelan to be the preservation of an ultra-oligotrophic condition. Additional TP loading to Lake Chelan (over the 1986-87 load) was considered to be acceptable only if there is less than a five percent chance that such additions will cause in-lake TP concentrations to exceed 4.5 μgP/L.

The Lake Chelan Water Quality Committee is now faced with the task of evaluating various alternatives for future development within the basin with respect to meeting the management goal identified by Patmont *et al.* (1989). The purpose of this memorandum is to identify the maximum allowable TP loads from controllable external sources in the basin and clarify how the information contained in Patmont *et al.* (1989) can be used.

Section 303(d) of the Clean Water Act requires the states to establish TMDLs for "water quality limited" waterbodies. While Lake Chelan is not currently considered to be water quality limited with respect to eutrophication, the potential for additional TP loads to cause violation of the management objective needs to be addressed. By identifying the TMDL and providing various options for WLAs and LAs, this memo provides the Lake Chelan Water Quality Committee with a tool for planning future growth and preventing degradation of the lake.

LOAD ALLOCATION FOR THE LOWER BASIN IF UPPER BASIN LOADS REMAIN CONSTANT

Patmont *et al.* (1989) presented an estimate for acceptable additional TP loading from future development, which could be considered a "load allocation" (LA) for future growth in the lower basin based on the assumption that upper basin loads would not change. The division between lower and upper basin lake and watershed areas for TP modeling is at the midpoint between Fields Point and Twenty-five Mile Creek, approximately 27 kilometers up-lake from the outlet dam and 8 kilometers up-lake from the sill between Wapato and Lucerne basins. A steady-state mass balance model for TP in the lower basin epilimnion was used to estimate the load allocation for future growth in the lower basin, over the existing load as of 1986-87, that would have less than a five percent chance of causing lower basin epilimnetic TP to exceed 4.5 μgP/L.

Patmont *et al.* (1989) estimated the acceptable (i.e. less than 5% risk) LA for future development TP loading to the lower basin during April-September, assuming upper basin loads remained at 1986-87 conditions, to be 0.5 KgP/day. The April-September period was chosen for the basis of estimating allowable loading increases because the lake was considered to be most sensitive to inputs during this period.

The April-September period has a higher average external loading rate than the annual average because of large inputs from spring snow-melt. Therefore, it is realistic to expect that if a target load can be achieved during April-September, it could also be achieved on an average annual basis. Therefore, we recommend the LA for future development be applied on an annual basis.

The use of annual average loads is supported by Patmont *et al.* (1989) for estimating the allowable amount of development that would meet the LA for future growth. Therefore, all loads, regardless of season, may be included in the analysis. The remaining discussion will be based on implementation of the TMDL and LAs as average annual loads.

LOAD ALLOCATIONS FOR THE LOWER BASIN IF UPPER BASIN LOADS INCREASE

Since the TP modeling presented by Patmont *et al.* (1989) is based on the assumption that upper basin loads will remain constant, additional modeling is required if upper basin external loads change. For example, additional TP loads to the upper basin may occur if fish net pens are assigned a WLA in the upper basin.

An annual steady-state mass balance model of the upper and lower lake basins is presented below to estimate the relative influence that external loads to the lower and upper basins have on lower lake TP concentrations. The use of an annual model is further justified for evaluating the influence of changing upper basin loads on water quality in the lower basin because of the relatively long hydraulic residence time (approximately nine years) in the upper lake basin. The annual mass balance for TP in the lower and upper basins is described as:

Lower Basin:

$$V_l(\delta P_l/\delta t) = W_l + X_l + Q_uP_u - Q_lP_l + E'(P_u-P_l) - \upsilon_lA_lP_l \qquad \text{(eqn 1)}$$

Upper Basin:

$$V_u(\delta P_u/\delta t) = W_u + X_u - Q_uP_u + E'(P_l-P_u) - \upsilon_uA_uP_u \qquad \text{(eqn 2)}$$

where:

subscripts "l" and "u" denote lower and upper basins, respectively, and

- V = volume (m^3)
- P = annual time- and volume-weighted whole-basin in-lake TP concentration (mgP/m^3)
- t = time (days)
- W = external TP load from local watershed (mgP/day)
- X = direct precipitation load to lake surface (mgP/day)
- Q = outflow discharge (m^3/day)
- E' = bulk longitudinal diffusion between basins (m^3/day)
- υ = apparent TP settling velocity (m/day)
- A = lake surface area (m^2)

The lower and upper basin mass balance equations can be solved simultaneously for the resulting TP concentration in the lower basin as (Chapra and Reckhow, 1983):

$$P_l = (\Omega_l\alpha_u + \Omega_u\beta_l) / (\alpha_l\alpha_u - \beta_l\beta_u) \qquad \text{(eqn 3)}$$

where:

$$\Omega_l = (W_l + X_l) / V_l$$
$$\Omega_u = (W_u + X_u) / V_u$$
$$\alpha_l = (Q_l + E' + \upsilon_l A_l) / V_l$$
$$\alpha_u = (Q_u + E' + \upsilon_u A_u) / V_u$$
$$\beta_l = (Q_u + E') / V_l$$
$$\beta_u = E' / V_u.$$

The annual steady state model was calibrated to Lake Chelan by solving for E', υ_l, and υ_u since all other variables were directly estimated and presented in Patmont *et al.* (1989). The first step was to solve for υ_l assuming that annual E' was equal to the April-September value in Table 6.2 of Patmont *et al.* (1989). The resulting υ_l was found to be not significantly different from zero, therefore, υ_l was assumed to equal zero and the annual calibration of E' was calculated as the only unknown of the steady-state solution of equation 1. Then the apparent TP settling velocity in the upper basin was calculated as the only unknown in the steady state solution of equation 2. In contrast to the lower basin, TP settling in the upper basin is highly significant, and the difference in settling between the two basins can probably be explained by the relatively large particulate P load to the upper basin from sources far up-lake (i.e. mainly the Stehekin River and Railroad Creek). A summary of all annual model calibration parameters is presented in Table 1.

The critical external annual TP load from the lower basin ($W_{l\text{-}crit}$), assuming that upper basin external loads do not change is found by rearranging equation 3 (with $P_l = P_{l\text{-}crit} = 4.5$ mgP/m^3):

$$W_{l\text{-}crit} = V_l \{[P_{l\text{-}crit}(\alpha_l\alpha_u - \beta_l\beta_u) - \Omega_u\beta_l] / \alpha_u \} - X_l$$

(eqn 4).

Similarly, the critical external annual TP load to the upper basin ($W_{u\text{-}crit}$), assuming that lower basin external loads do not change is found:

$$W_{u\text{-}crit} = V_u \{[P_{l\text{-}crit}(\alpha_l\alpha_u - \beta_l\beta_u) - \Omega_l\alpha_u] / \beta_l \} - X_u$$

(eqn 5).

The relative influence that lower basin and upper basin external loads have on the lower basin TP concentration can then be found by comparison of the additional loads to each basin which would cause the same increase in P_l to $P_{l\text{-}crit}$ = 4.5 mgP/m^3:

$$RATIO = (W_{l\text{-}crit} - W_l) / (W_{u\text{-}crit} - W_u)$$

(eqn 6).

where RATIO represents the decrease in the lower basin LA for each unit increase in upper basin external loads over the existing (1986-87) conditions.

The critical external loads to the lower basin ($W_{l\text{-}crit}$) and upper basin ($W_{u\text{-}crit}$), found using equations 4 and 5, are 13.0 ± 6.8 KgP/day and 47.0 ± 14.6 KgP/day, respectively, with each critical load based on the assumption that loading to the other basin remains at 1986-87 levels. For comparison, the existing (1986-87) external loads to lower (W_l) and upper (W_u) basins were 6.3 ± 3.5 KgP/day and 34.1 ± 3.5 KgP/day, respectively.

Equation 6 reveals that the value of RATIO is 0.52 ± 0.12 (dimensionless). This means that a 1 KgP/day increase in external load to the upper basin causes the same change in lower basin TP concentration as a 0.52 KgP/day increase in lower basin loading. As discussed above, the difference in effect can be explained by the relatively large sedimentation of TP in the upper basin. The lower basin LA should therefore be reduced 0.52 KgP/day for each 1 Kg/day LA allowed for increase in upper basin external loading over the 1986-87 conditions.

SUMMARY OF TMDL AND LAs

The TMDL represents the sum of all WLAs and LAs, including the LA for existing land use in the lower basin, LAs for future development in the lower and upper basins, a constant background LA, and any WLAs for point sources which will meet the management objective. While the management objective is fixed (less than 5% chance of exceeding 4.5 μgP/L), the magnitude of the TMDL that meets that objective depends to a certain extent on whether increased loading is allowed in the upper basin. Because of the significant TP settling in the upper basin, the TMDL increases, while still meeting the management objective. However, the LA for future development in the lower basin watershed would decrease by 0.52 KgP/day for each 1 KgP/day increase in the upper basin LA, as discussed above.

A summary of the realistic range of the TMDL and various allowable combinations of load allocations is presented in Table 2. The LA combinations considered range between three options:

- **Option 1:** use the entire allowance for future growth in the lower basin, which would limit growth in the upper basin to zero;
- **Option 2:** mixture of future growth LAs in the lower and upper basin; and
- **Option 3:** use the entire allowance for future growth in the upper basin, which would reduce the LA for future growth in the lower basin to zero and limit lower basin loads to the existing 1986-87 loads.

The most likely choice will probably be close to the first option, but may lie somewhere within option 2, depending on how large a LA is allowed for growth in the upper basin, as presented in Table 2.

RECOMMENDED METHOD OF ESTIMATING EXTERNAL LOADS FOR FUTURE DEVELOPMENT SCENARIOS

In order to minimize uncertainty in estimates of external loading for various future development scenarios when loading from existing land use is already estimated, Reckhow and Chapra (1983) recommend: 1) estimating the net change in load from the watershed areas which would be changed under a given scenario; and 2) adding that net change to the load estimated for the existing land use. This approach is applicable to Lake Chelan since the land use area expected to change is small in comparison to the land use area that is expected to remain constant.

As part of the Lake Chelan Water Quality Plan that is being developed by the Lake Chelan Water Quality Committee, various alternative future development scenarios are being considered. The steps involved in evaluating TP loading changes for each scenario with respect to TP load allocations would be:

1) identify the size of the LA (and WLA if applicable) for future development in the upper basin (between 0 and 0.96 KgP/day)

2) determine the size of the LA (and WLA if applicable) for future development in the lower basin in KgP/day =

   0.5 - [0.52 * LA for upper basin growth]

3) develop the future scenario such that the estimated net increase in loading from altered watershed areas and point sources in the future scenario does not exceed the assigned LAs (and WLAs if applicable) for future development. Information in Tables 5.11 and 6.3 of Patmont et al. (1989) should be used to estimate TP loading changes from all land use changes relative to 1987. For example, the net change in loading from addition of residences on septic systems with enhanced regulations could be estimated from data in Table 6.3 of Patmont et al. as 0.18 KgP/day per 1,000 dwellings added since 1987. Similarly, if the houses were added on orchard land converted to residential use, the credit for reducing agricultural inputs could be estimated from data in Table 5.11 of Patmont et al. as 0.10 KgP/day per square kilometer (38 KgP/Km^2-year divided by 365 days/year) of land converted.

CONCLUSIONS AND RECOMMENDATIONS

- The division between lower and upper basins for compliance with the TMDL should be interpreted as the mid-point between Fields Point and Twenty-five Mile Creek.

- The direct TP load to the lower basin from the watershed and in-lake anthropogenic activities should not exceed 0.5 KgP/day more than the existing load (6.9 KgP/day during April-September; 6.3 KgP/day annually) estimated by Patmont et al. (1989) in the 1986-87 study year. Therefore the LA (and WLA if applicable) for net increase from future development in the lower basin is 0.5 KgP/day assuming that upper basin external loads do not increase.

- If external TP loading to the upper basin increases above the existing load estimated by Patmont et al. (1989) then the lower basin LA (and WLA if applicable) for future development shall decrease by 0.52 KgP/day for each 1 KgP/day LA allowed for net increase from future development in the upper basin over the 1986-87 condition.

- For the purpose of evaluating various future watershed development scenarios with respect to the TMDL, the total external load to Lake Chelan from a given scenario should be based on estimated changes in loading added to or subtracted from the existing (1986-87) loads estimated by Patmont et al. (1989). In other words, the net change in annual loading from a given development scenario should be estimated and should not exceed the LA (and WLA if applicable) assigned for net increase from future development.

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Table 1. Summary of annual TP model parameters for calibration to 1986-87 data.

Model Symbol	Value	Units	Source
P_l	3.70 ± 0.25	mgP/m^3	(1)
P_u	2.89 ± 0.26	mgP/m^3	"
Q_l	$5.09e+6 \pm 2.84e+5 m^3/day$		(2)
Q_u	$5.03e+6 \pm 2.84e+5$	m^3/day	"
W_l	$6.28e+6 \pm 3.45e+6$	mgP/d	(3)
X_l	$3.64e+6 \pm 2.47e+6$	mgP/d	"
W_u	$3.41e+7 \pm 3.54e+6$	mgP/d	"
X_u	$6.52e+6 \pm 3.29e+6$	mgP/d	"
E'	$6.98e+6 \pm 6.70e+6$	m^3/day	(4)
A_l	$5.33e+7 \pm 5.33e+5$	m^2	(5)
A_u	$8.15e+7 \pm 8.15e+5$	m^2	"
υ_l	$0 \pm 3.89e-2$	m/day	(6)
υ_u	$1.35e-1 \pm 3.55e-2$	m/day	(7)
V_l	$3.02e+9 \pm 1.51e+8$	m^3	(8)
V_u	$1.64e+10 \pm 8.22e+8$	m^3	"

DATA SOURCES:
1) calculation after Patmont et al. (1989).
2) Table 5.1 of Patmont et al. (1989).
3) Table 5.9 of Patmont et al. (1989).
4) steady-state solution of equation 1.
5) Table 6.2 of Patmont et al. (1989).
6) found to be not significant, therefore assumed equal to zero for model calibration of E'
7) steady-state solution of equation 2.
8) calculation after Kendra and Singleton (1987).

Table 2. Summary of various options for load allocations for future development in the lower and upper basins.

	Load Allocation For Existing (1986-87) Land Uses in the Lower Basin	Load Allocation For Future Growth in the Lower Basin	Load Allocation For Future Growth in the Upper Basin	Load Allocation for Background Load from Upper Basin Watershed and Precipitation	TMDL= Sum of Lower and Upper Basin External and Background Loads
	KgP/d	KgP/d	KgP/d	KgP/d	KgP/d
OPTION 1: No Growth in Upper Basin:	6.3	0.50	0.00	44.2	51.0
OPTION 2: Mixture of Growth in Lower and Upper Basins:	6.3	0.47	0.05	44.2	51.0
	6.3	0.45	0.10	44.2	51.0
	6.3	0.40	0.20	44.2	51.1
	6.3	0.34	0.30	44.2	51.1
	6.3	0.29	0.40	44.2	51.2
	6.3	0.24	0.50	44.2	51.2
	6.3	0.19	0.60	44.2	51.3
	6.3	0.14	0.70	44.2	51.3
	6.3	0.08	0.80	44.2	51.4
OPTION 3: No Growth in Lower Basin:	6.3	0.00	0.96	44.2	51.5