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A Classification of Pacific Northwest Reservoirs with Respect to Nutrient Processing

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(Cover Photos: Top - Lake Billy Chinook, a Xeric West reservoir in eastern Oregon; bottom - Bumping Lake, a Western Forested Mountains reservoir in Washington).

TABLE OF CONTENTS

Page

Abstract

To begin the process of developing nutrient criteria for Pacific Northwest reservoirs, 48 reservoirs were sampled in Oregon, Washington and Idaho during summer 2002. The National Inventory of Dams lists 2419 dams in the Pacific Northwest. Over 75% of them represented reservoirs that were less than 30 hectares and were not considered in this study. After removing these small reservoirs and other non-target sites, there were 328 reservoirs that met our target criteria. The 48 sample reservoirs were selected from these 328 target reservoirs using a systematic, randomized design with Omernik Nutrient Ecoregions (Xeric West or Western Forested Mountains) as a stratification variable.

Total phosphorus (TP) concentrations were higher and Secchi depths lower in the Xeric West relative to the Western Forest Mountains. Total nitrogen (TN) and chlorophyll-a concentrations were not significantly different between the two Ecoregions. All four nutrient variables were strongly correlated with each other in both Ecoregions. However, reservoir purpose class was not correlated with nutrient concentrations.

In the Western Forested Mountains, TP concentrations were very strongly related to measures of ionic strength (e.g., base cations, alkalinity, conductivity); an indication that there is a natural TP gradient related to watershed geology/soils. In the Xeric West TP was less strongly related to potassium and sodium and not related at all to the other indicators of ionic strength. The source of TP could be some specific geologic source that is only related to potassium or sodium or it could be associated with fertilizers that are high in potassium.

Principal components analysis and cluster analysis were performed on reservoirs in the Western Forested Mountains and the Xeric West. Analysis did not reveal any clear classification of reservoirs in the WFM. In the Xeric West 5 variables were (potassium, alkalinity, absorbence at 326 nm, turbidity and chlorophyll) used to identify 4 clusters of reservoirs. A reservoir typology resulting in 3 categories was developed from these four clusters.

Category 1 – Low ionic strength, high transparency, low absorbence, low turbidity, low chlorophyll.

Category 2 – Moderate ionic strength, moderate transparency, moderate absorbence, moderate turbidity due either to algae or particulate matter.

Category 3 – High ionic strength, very high absorbence, very low transparency due to algal and/or nonalgal turbidity.

These three classes differed in distributions of total P concentration and water transparency. Total N and chlorophyll values were not different among categories.

The use of Nutrient Ecoregion provides a useful classification variable in categorizing reservoirs in the Pacific Northwest. However, it appears that the Level III Ecoregion Eastern Cascades should be placed into the Xeric West Nutrient Ecoregion when classifying reservoirs. The reasons for this are unclear but may have to do with geology or precipitation.

Future studies on reservoir nutrient dynamics in the Pacific Northwest should explicitly take nonalgal turbidity into account to differentiate between the effects of nutrients and water transparency on algal growth.

Introduction

According to the U.S. Environmental Protection Agency=s (EPA=s) 1996 report to Congress, a large percentage of U.S. lakes and reservoirs are water quality impaired, many due to excess nutrients. In order to address this problem EPA has devised a strategy for the development of regional nutrient criteria (USEPA 1998). Implicit in the strategy is the recognition that excess nutrients are a major cause of water quality impairment in the United States. The strategy also acknowledges that because of diverse geology, climate, and morphometry, single national nutrient criteria for lakes and reservoirs are not appropriate. EPA's current approach for developing nutrient criteria for lakes and reservoirs involves the following steps (Kennedy 2000):

1. Establish regional technical assistance groups.
2. Delineate nutrient ecoregions.
3. Classify or group lakes/reservoirs using non-nutrient parameters.
4. Establish an appropriate nutrient related database.
5. Establish reference conditions for each group or classification.
6. Develop nutrient criteria for each group or classification.

Although the same basic physical, chemical and biological processes determine nutrient dynamics in lakes and reservoirs, the age, morphometry, location in the drainage basin and hydrological characteristics of reservoirs make them a unique ecosystem (Cooke and Kennedy, 1989, Thornton et al. 1990). As such developing a classification of reservoirs with respect to nutrient processing must take the unique nature of these systems into account (Straskraba, 1993). This report describes the methods and results of a study of nutrient levels and classification of 48 randomly selected reservoirs in the Pacific Northwest states of Oregon, Washington and Idaho. In previous work we have demonstrated that it is possible to classify lakes using Level III Ecoregions (Vaga and Herlihy 2004, 2005).

Methods

Site selection and population definition

Reservoirs range greatly in size and type across the Pacific Northwest from small farm ponds to giant hydropower/flood control reservoirs on the Columbia River. For this study, the target population of interest was restricted to specific reservoir types and size range. The population of interest only includes reservoirs with a surface area between 30 and 10,000 hectares. Target types include hydropower, flood control, water supply, irrigation, and recreation reservoirs. Mine tailing, wastewater effluent, debris control, run-of-the-river, and enhanced lake reservoirs are not part of the target population. Determination of type was based on the National Inventory of Dams purpose designations. Enhanced lake reservoirs were defined as lakes in which the dam height is less than 25% of the maximum depth of the reservoir.

Reservoir location was expected to be an important factor in explaining nutrient concentrations so ecoregion was used as a stratification variable in site selection. To aid in developing nutrient criteria at the national level, EPA has delineated the conterminous U.S. into nutrient ecoregions according to geologic and climactic characteristics (Omernik 1998). Portions of three nutrient ecoregions lie within Region 10: Western Forested Mountains (WFM), Xeric West (XW), and Willamette and Central Valleys. Reservoirs within Region 10's portion of the Willamette and Central Valley nutrient ecoregion are not common and for this project were considered part of the Western Forested Mountains region. Thus there were two ecoregion strata for site selection.

The sample frame or explicit list of the target population from which sites were selected was the list of all reservoirs in the National Inventory of Dams for Oregon, Washington, and Idaho. Based on this frame, there are 2,417 dams in Oregon, Washington, and Idaho (Table 1). Reservoirs outside the type and size cutoffs described above were removed from the frame. Only 328 of the 2,417 reservoirs in the Pacific Northwest met our target criteria. The majority of dams in the database were non-target due to small surface area (Table 1). To make inferences to all 328 reservoirs in this target population, sample reservoirs were selected from this set using a stratified, randomized design.

The desired sample size was 48 reservoirs, 24 from each of the two ecoregion strata. To ensure a broad geographic spread of reservoirs across the study area, level III ecoregions (Omernik, 1987) were used to define spatial clusters. The Northern Basin and Range ecoregion was split into Oregon section and Idaho sections because the region is considerably larger than other Level III ecoregions in Region 10. The 328 reservoirs in the sample frame were randomly sorted within level III ecoregion and then level III ecoregion blocks randomly sorted within each of the two nutrient ecoregion strata. Sites were over sampled so that there would be alternate reservoirs. Therefore, 48 reservoirs were selected from each strata, 24 primary and 24 secondary (alternates). After a random start, reservoirs were picked an interval of N/48 from the randomized frame of all reservoirs in the strata (N is the total number of reservoirs in the strata).

Of the 48 primary randomly selected reservoirs, 33 were successfully sampled in the summer of 2002. Of the 15 lakes not sampled, 6 were due to access problems (private property, no launch site, or remoteness), 2 were dry, 2 were enhanced, 1 had no dam, and 3 were less than 30 ha when visited in the field. In addition, one reservoir wasn't sampled due to time constraints. Thus 31% (15/48) of the 328 reservoirs in the target population were not really target in the real world. If a primary reservoir could not be sampled, one of the secondary reservoirs from the same Level III ecoregion was sampled. If that reservoir could not be sampled another secondary reservoir from the same Level III ecoregion was sampled. If the pool of secondary reservoirs within a Level III ecoregion was exhausted, the original sample frame was revisited and a tertiary reservoir was selected from the same Level III ecoregion.

In three cases this process was not followed.

1. One Idaho Batholith reservoir: In the Idaho Batholith Level III ecoregion one primary reservoir was not sampled because of time constraints (Fish Creek Reservoir). A secondary reservoir with easier access was sampled in its place (Brundage Reservoir).
2. Two Northern Rockies reservoirs: In the Northern Rockies Level III ecoregion the pool of secondary reservoirs was exhausted and no suitable tertiary reservoirs were identified in the sample pool. One reservoir located partially in the Columbia Plateau and the Northern Rockies ecoregions was selected from the Columbia Plateau's secondary list. Laurence Lake was selected from the Cascade Level III ecoregion to replace the other missing Northern Rockies reservoir.
3. One Puget Lowland reservoir: The primary and secondary list was exhausted, and due to time constraints, a reservoir close to Portland was sampled (Henry Hagg Lake, tertiary, Willamette Valley ecoregion)

Inspection of the data, e.g. cations suggested that East Cascade reservoirs were far more similar to reservoirs in the Xeric West that those in the Western Forested Mountains. Under similar considerations one reservoir (Thief Valley, east end of the Blue Mountains Ecoregion) which was originally in the WFM was placed into the Xeric West. Long Lake (WFM) was deleted from analysis because it is currently 303(d) listed for nutrients due to high nutrient inputs from point sources. In addition, after analysis of watershed versus dam location it was determined that two reservoirs (Conconully, Leader) are actually in the WFM rather than the XW. The resulting sample included 27 Xeric west reservoirs and 20 Western Forested Mountains (Fig. 1, Table 2).

Table 1. Sample Frame size and target population size for Pacific Northwest Reservoirs. Non-target reservoirs were those reservoirs excluded from the Frame because they did not meet criteria. Of the 2419 reservoirs in NID only 328 met the criteria. About two-thirds of those were in the Western Forested Mountains Ecoregion.

Total Number in Inventory= 2419	
Non -Target Reservoirs	
Too Small (< 30 ha)	1828
Non-Target Types	122
Enhanced Lakes	71
Duplicate/Auxiliary Lakes	53
Inaccessible	7
Other	10
Total Non-Target	2091
Target Reservoirs = 328	
W. Forested Mt. Ecoregion	220
Xeric West Ecoregion	108

Table 2. List of sampled reservoirs with location and surface area. Numbers refers to reservoir locations in Figure 1. Most sensitive use: HM: Hydrologic Management, RC: Recreation, WS: Water Supply.

	WESTERN FORESTED MOUNTAINS				
No	**Lake Name**	**Area**	**LAT**	**LONG**	**Use**
1	Brundage Res	87.0	45.0	-116.13	HM
2	Bumping Lake	527.3	46.8	-121.30	RC
3	Clear Lake	56.7	46.6	-121.27	RC
4	Conconully Res	133.6	48.5	-119.75	RC
5	Diablo Lake	400.7	48.7	-121.13	RC
6	Fern Ridge Res	3788.0	44.1	-123.29	RC
7	Galesville Res	257.0	42.8	-123.18	WS
8	Henry Hagg Res	468.2	45.4	-123.21	WS
9	Judy Res	56.7	48.4	-122.19	WS
10	Lake Simtustus	218.5	44.6	-121.23	RC
11	Laurence Lake	64.8	45.4	-121.66	RC
12	Leader Lake	74.9	48.3	-119.70	RC
13	Mayfield Res	910.6	46.5	-122.59	RC
14	N Fork Clackamas	141.6	45.2	-122.28	RC
15	Ochoco Res	493.7	44.3	-120.73	RC
16	Prineville Res	1449.0	44.1	-120.78	HM
17	Sage Hen Res	96.3	44.3	-116.19	WS
18	Skookumchuck Res	218.5	46.7	-122.72	HM
19	Toketee Res	41.3	43.2	-122.42	RC
20	Willow Creek	130.3	42.4	-122.44	WS
XERIC WEST					
21	Alexander Res	494.9	42.6	-111.70	HM
22	Barry Res	60.7	42.1	-119.53	HM
23	Ben Ross Res	142.9	44.5	-116.44	WS
24	Black Canyon Res	445.2	43.9	-116.44	HM
25	Blue Creek Res	76.1	42.3	-116.18	WS
26	Bray Lake	82.6	43.0	-114.88	HM
27	Bryant Mt. Res	48.6	42.1	-121.33	HM
28	Cedar Creek Res	424.9	42.2	-114.88	HM
29	Chickahominy	214.1	43.5	-119.61	HM
30	Daniels Res	151.8	42.3	-112.44	HM
31	Grasmere Res	31.6	42.3	-115.90	WS
32	JC Boyle Res	170.0	42.1	-122.04	RC
33	Kern Res	43.7	42.9	-118.78	HM
34	Little Blue Creek	53.8	42.2	-116.12	WS
35	Mann Creek Res	127.5	44.3	-116.89	RC
36	Mud Lake	68.0	42.2	-119.72	HM
37	Muddy Creek Res	78.9	42.2	-120.52	HM
38	Paddock Valley Res	542.3	44.2	-116.60	HM
39	Priday Res	85.8	42.3	-119.90	HM
40	Sand Creek Res	31.6	44.2	-111.61	RC
41	Scooteney Res	617.2	46.6	-119.03	HM
42	Stone Res	100.0	42.0	-112.69	WS
43	Thief Valley Res	373.5	45.0	-117.78	RC
44	Trail Storage Pond	104.8	43.0	-115.32	HM
45	Upper Rock Creek	155.4	42.6	-119.31	HM
46	Warmsprings Res	1862.0	43.5	-118.21	RC
47	Weston Creek Res	45.3	42.1	-112.13	WS

Field and laboratory methods

Reservoirs were visited during the summer growing season, May through September, 2002. Reservoirs were sampled by boat and those from different nutrient ecoregions were sampled on a rotating schedule as much as logistically possible to avoid seasonal bias. The deepest location in each reservoir was found by starting at the dam and using an electronic depth finder. A water sample and in situ measurements were collected at the deepest spot in each reservoir. In situ profiles of temperature, dissolved oxygen, pH, Turbidity, redox potential, light extinction coefficient, and conductivity were collected using a Hydrolab Sonde 4a meter. Secchi depth was determined as the average of the disappearance and reappearance depths of a 20 cm Secchi disk. Two, 1 L water samples were collected from 1 m depth using a 2.5 L, Model 1010X Niskin bottle. One sample was preserved by acidification to pH < 2 for analysis of total nitrogen and phosphorus. The other sample was filtered with a Whatcom glass fiber filter that had a nominal pore size of 0.7 µm. The filter paper was frozen, kept in the dark and analyzed for chlorophyll-a. The filtrate was kept and used for analysis of anions, base cations, DOC, alkalinity, and light absorbence. All water samples were kept cold and in the dark until analysis.

n the lab, chlorophyll-a was determined fluorometrically. Base cations were analyzed by flame atomic absorption spectrometry and sulfate and chloride by ion chromatography. Alkalinity was determined by Gran titration, and DOC by carbon analyzer. Total phosphorus and nitrogen were analyzed by persulfate digestion and colorimetry. Light absorbence at 325 and 440 nm was measured with a spectrophotometer.

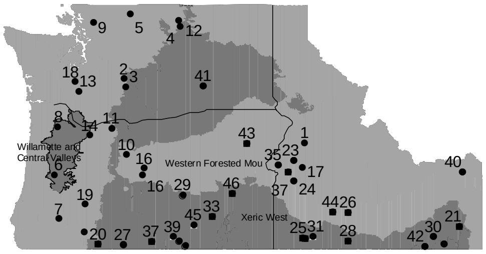

Figure 1. Location of the 47 reservoirs used in this study. Numbers refer to reservoir number in Table 2.

Field measurement of reservoir physical habitat and substrate composition were made using a condensed form of the U.S. EPA EMAP lake protocols (Baker et al., 1997). Sampling locations were set up following a random start at 10 equal interval shoreline stations around the reservoir. Percentage category estimates were made at each station for substrate classes (clay, sand, cobble/gravel, boulder, bedrock), vegetation cover classes (barren, herbs, shrubs, trees), and macrophyte cover classes (submergent, emergent, floating) as well as presence/absence of human influence categories. These data were analyzed by averaging the 10 measurements together to calculate shoreline cover estimates for the entire reservoir. In addition, depth below maximum pool estimates were made by comparing lake level at the time of sampling to shoreline evidence of maximum reservoir conditions.

Data Analysis

Data were entered into Excel spreadsheets and converted into SAS databases for analysis. As is typically observed for water chemistry data, the data are not normally distributed. Most water chemistry variables are highly skewed. For all statistical analyses, chemical variables were log10 transformed as were reservoir surface area and maximum depth. Shoreline percentage data and Secchi depth were not transformed. All correlation analyses were done using Spearman rank correlations in SAS.

A two-way analysis of variance (ANOVA) was used to test for differences in nutrient concentration due to ecoregion (Xeric West versus Western Forested Mountain) and reservoir purpose (Hydrologic management, Drinking water, or Recreation). Reservoir purpose was taken from the National Inventory of Dams database. Many reservoirs were coded with multiple purposes. The hydrologic management class includes hydropower, irrigation, or navigation categories. A single purpose class was assigned to each reservoir as a "most-sensitive" purpose rating sensitivity as Water supply > Recreation > Hydrologic management. In other words if there were any one purpose listed as water supply, the reservoir was coded as water supply even though it may have been also listed for other purposes. ANOVAs were run in SAS using PROC GLM.

To get at an initial indication of possible reservoir clusters or types, a principal components analysis (PCA) was performed on the major reservoir typology variables. Axis or factor scores were then clustered via cluster analysis to look for groups of reservoirs. PCA was done using SAS PROC FACTOR, method=PRINCOMP. Cluster analysis were
done using PC-ORD using the Flexible Beta method (beta=-0.5).

Results

Ecoregional Patterns

Of the total number of reservoirs included in this analysis, 27 were in the Xeric West and 20 were in the Western Forested Mountains Ecoregion. By most sensitive purpose class, 11 were water supply, 17 were recreation, and 19 were hydrologic management reservoirs. Most of the hydrologic management reservoirs were in the Xeric West and most of the recreation reservoirs were in the Western Forested Mountains (Table 2).

The use of Nutrient Ecoregion as a classification variable for reservoirs proved to be useful in characterizing reservoirs (Table 3). Reservoirs in the WFM tended to be larger, deeper and of greater volume that those in the XW. However, distributions of reservoir surface areas within each of the two ecoregions were virtually identical. Similarly, there was little difference in surface area across purpose class. In a two-way ANOVA, mean surface areas across both ecoregion and purpose class were not significantly different ($p > 0.25$). Maximum reservoir depths, however, were significantly ($F=7.0$, $p=0.01$) higher in the Western Forested Mountains than the Xeric West (Tables 3, 4). Depths across purpose class were not significantly different.

Water transparency as measured by extinction coefficient and Secchi depth were greater in the WFM (Table 3). Reservoirs in the XW were more turbid that in the WFM. Surface water temperatures tended to be greater in the XW. Reservoirs in the WFM tended to be more dilute that in the XW. Median conductivity, alkalinity and ANC were all much lower in the WFM than in the XW (Table 3). Chlorophyll concentrations were higher in the XW as was DOC. Reservoirs in the XW were higher in DOC (Abs325) and humics (Abs440) than in the WFM (Table 3).

Cations (K, Na, Ca, Mg) were all higher in the XW reservoirs as compared with WFM reservoirs. Anions (CL, SO_4) were also higher in the XW (Table 3).

The primary nutrient criteria variables, total phosphorus (TP), total nitrogen (TN), chlorophyll-a, and Secchi depth, and their distributions within each nutrient ecoregion are shown in Figures 4 - 7. Mean TP concentrations were significantly higher in the Xeric West Ecoregion and in Hydrologically managed reservoirs (Tables 3, 4, Fig. 4). TN concentrations showed no difference across either ecoregion or purpose class (Table 4, Fig. 5). Chlorophyll-a concentrations were higher in hydrologically managed reservoirs but showed no ecoregion effect whereas Secchi depth was higher in the Western Forested Mountains but showed no reservoir purpose effect (Table 4, Figs, 6, 7). For all four variables, the ecoregion-purpose interaction terms in the ANOVA were not significant.

Turbidity, light extinction coefficient, and absorbence at 325 nm (DOC) and 440 nm (fulvic acids) were also analyzed. The correlation matrix of the relationships among these variables shows that in both Ecoregions the variables are highly correlated with each other (Table 5). In the Xeric West there were very high correlation coefficients (r>0.8) for the relationships among the transparency variables (Secchi, extinction, absorbence) and between transparency and turbidity. The relationship between extinction coefficient and chlorophyll-a was significant but much lower (r~0.5) indicating that transparency in the Xeric West is affected by abiotic turbidity in addition to algal production (Fig. 8).

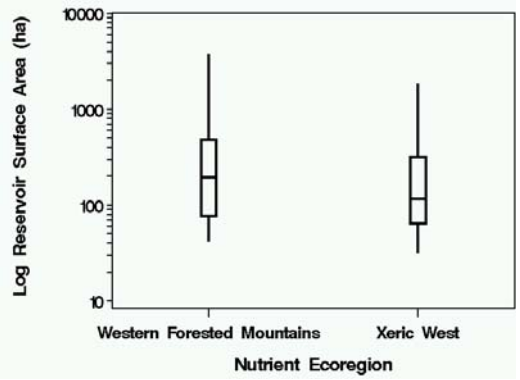

Figure 2. Box and whisker plot of reservoir surface area by nutrient ecoregion. Boxes show the interquartile range and median, whiskers the minimum/maximum values.

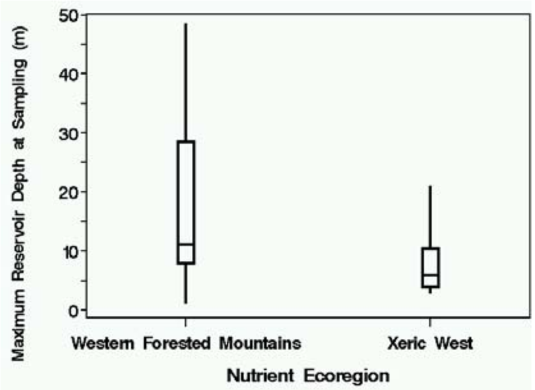

Figure 3. Box and whisker plot of maximum depth by nutrient ecoregion. Reservoirs in the Western Forested Mountains are significantly deeper than those in the Xeric West.

On the other hand, in the Western Forested Mountains, transparency is more strongly related to chlorophyll-a (r~0.8), indicating a more important role for algal production in transparency. This hypothesis is also supported by the scatterplot of Secchi depth versus turbidity (Fig. 9). With one exception, the Xeric West reservoirs have almost a

Table 3. Median (± 1 SE) values for physical and chemical characteristics of reservoirs sampled in the Western Forested Mountains and Xeric West. Volume is (m^3 x 10^6), depth is maximum depth and ions are (uEq/L).

	WFM		XW	
Variable	Median	se	Median	se
Area (ha)	218.5	180.0	104.8	75.8
Volume	36.7	57.5	6.3	27.7
Depth(m)	11.2	2.7	6.0	0.9
Ext (m^{-1})	0.5	0.1	2.1	0.4
Secchi (m)	3.4	0.5	0.7	0.3
Turb(NTU)	0.9	1.1	14.7	8.7
Temp (°C)	17.4	0.8	22.0	0.6
pH	7.9	0.2	8.4	0.1
Eh (mV)	340.0	18.5	318.0	6.6
Dosat (%)	97.0	3.3	96.9	5.1
TP (ug/L	23.0	13.6	109.0	43.7
TN (ug/L)	213.2	54.3	430.9	46.3
K	22.8	6.9	88.2	13.7
Na	187.0	77.7	357.6	140.2
Ca	289.4	75.5	524.0	116.2
Mg	157.7	48.8	244.1	213.0
SO_4	43.6	49.1	77.2	63.4
Cl	64.1	14.7	101.8	147.7
Alk (mg/L)	28.2	7.8	57.6	11.5
Cond(uS)	60.0	18.3	113.4	41.4
ANC(uEq/L	563.6	155.5	1151.5	230.0
Chla (ug/L)	4.6	3.1	7.5	27.8
DOC(mg/L)	2.2	1.6	11.7	2.8
Abs325	50.0	15.2	267.3	87.4
Abs440	9.3	2.5	55.8	26.8

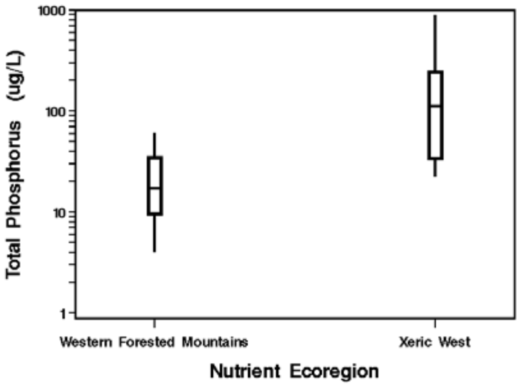

Figure 4. Box and whisker plot of total phosphorus by nutrient ecoregion. Total phosphorus is significantly higher in the Xeric West reservoirs.

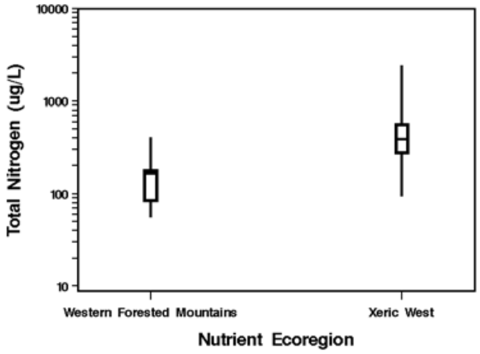

Figure 5. Box and whisker plot of total nitrogen by nutrient ecoregion. Total nitrogen concentrations are not significantly different between ecoregions.

straight-line relationship between turbidity and Secchi depth (the one outlier is a reservoir with chlorophyll-a=519 ug/L which is responsible for the 0.15 m Secchi depth). In the Western Forested Mountains, the plot isn't nearly as linear, indicating non-turbidity factors influencing Secchi depth.

Reservoirs with high TP tend to have high TN (Fig. 10). Reservoirs in the Xeric West tend to have higher concentrations of both TP and TN. However, the slope of the log(TN) - log(TP) regression was significantly ($p < 0.05$) higher in the WFM. Chlorophyll-a concentrations increased with TP in both ecoregions (Fig. 11) but again the slopes were significantly lower in the XW.

Chlorophyll also increased with TN in both nutrient ecoregions (Fig. 12). Secchi transparency decreased with increasing TP in both ecoregions (Fig. 13). However, the lowest transparencies observed in the Xeric West were not due to chlorophyll but non-algal turbidity.

TP is often used a measure of trophic status. A commonly used scheme is to use TP concentrations of 10, 30 and 50 ug/L as the cutoffs between oligotrophic-mesotrophic, mesotrophic-eutrophic, and eutrophic-hypereutrophic lakes. Using this scheme, none of the reservoirs in the Xeric West are oligotrophic, and 62.5% of the reservoirs are hypereutrophic. In contrast, in the Western Forested Mountains, one-third of the reservoirs are oligotrophic and 25% are hypereutrophic.

As these data are from a random sample of all Pacific Northwest reservoirs, these percentages should reflect conditions in all 328 reservoirs that met our target criteria. Extrapolating the values in Table 3 to all reservoirs in the PNW using the two Nutrient Ecoregion estimates and the total number of reservoirs in each ecoregion strata (Table 1), 22.3% are oligotrophic, 25% are mesotrophic, 3% are eutrophic, and 37.3% are hypereutrophic.

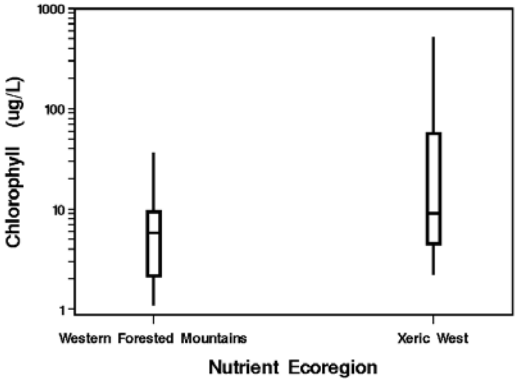

Figure 6. Box and whisker plot of chlorophyll-a by nutrient ecoregion. Chlorophyll concentrations were not significantly different between ecoregions.

Watershed Chemistry and Nutrients

Base cation concentrations are typically controlled by watershed geology/soils and weathering rates. There were clear differences between ion relationships between Nutrient Ecoregions. In the WFM correlations among most cations and anions were high and significant (Table 6). In the Xeric West, the divalent base cations (calcium and magnesium) are strongly related to each other and the monovalent base cations (sodium and potassium) are strongly related to each other but the two groups are not strongly related to each other.

These results suggest that in the Western Forested Mountains all of the base cations come from a similar source. In contrast, in the Xeric West there appears to be independent sources for these two groups of base cations .

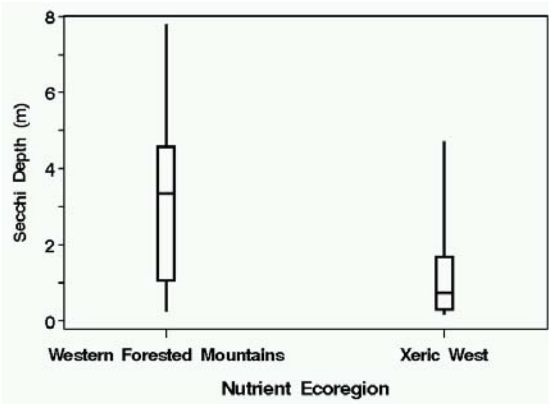

Figure 7. Box and whisker plot of Secchi depth by nutrient ecoregion. Reservoirs in the Western Forested Mountains are significantly more transparent that those in the Xeric West.

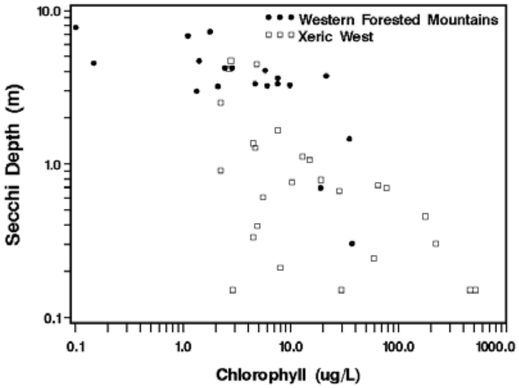

Figure 8. Relationship between Secchi depth and chlorophyll in Pacific Northwest reservoirs. The dependence of water transparency on chlorophyll is much stronger in the WFM as compared with the XW.

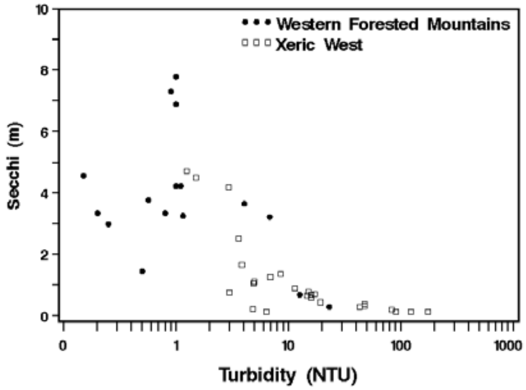

Figure 9. Relationship between Secchi depth and turbidity in Pacific Northwest reservoirs. Highest turbidities in the Xeric west are due to non-algal turbidity.

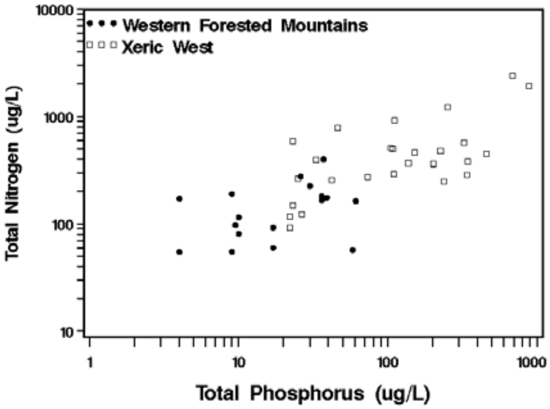

Figure 10. Relationship between total nitrogen and total phosphorus in Pacific Northwest reservoirs. Total nitrogen increases in both ecoregions with total phosphorus.

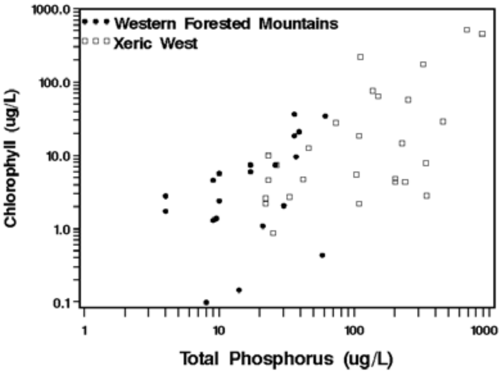

Figure 11. Relationship between chlorophyll and total phosphorus. Chlorophyll increases with increasing total phosphorus in both ecoregions.

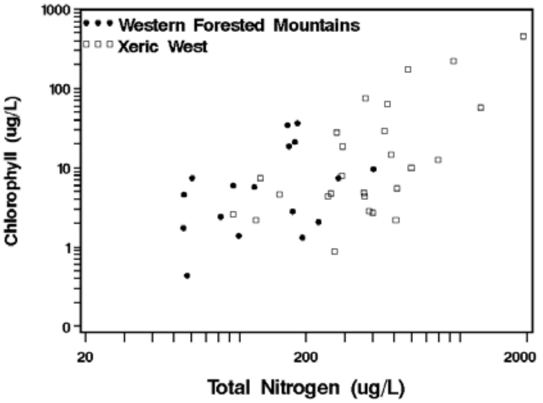

Figure 12. Scatterplot of chlorophyll versus total nitrogen. Chlorophyll increases with total nitrogen in both ecoregions.

Table 4. Two-way analysis of variance results on the effects of ecoregion and reservoir purpose class on nutrient criteria variables. Bold values were significant at $p < 0.05$.

Variable	Class	F	Means
Total Phosphorus	Ecoregion Reservoir Purpose Eco x Purpose Interaction	5.8 (0.021) 4.8 (0.013) 0.64 (0.53)	Xeric > W. For. Mt. Mng > Rec = Water n.s.
Total Nitrogen	Ecoregion Reservoir Purpose Eco x Purpose Interaction	3.5 (0.071) 2.0 (0.20) 0.50 (0.61)	n.s. n.s. n.s.
Chlorophyll-a	Ecoregion Reservoir Purpose Eco x Purpose Interaction	0.23 (0.63) 3.5 (0.039) 0.16 (0.85)	n.s. Mng > Water = Rec n.s.
Secchi depth	Ecoregion Reservoir Purpose Eco x Purpose Interaction	5.4 (0.026) 1.0 (0.37) 0.02 (0.98)	W. For. Mt > Xeric n.s. n.s.

Nutrient Ecoregion: Xeric=Xeric West, W. For. Mt. = Western Forested Mountains. Use: Mng=Hydrologic Management, Rec=Recreation, Water=Water Supply, n.s. = Not significant

In the WFM total P is highly correlated with all cations but not correlated with Sulfate and weakly correlated with Chloride (Table 6). In the XW total P is weakly correlated with Potassium and Sodium not correlated with any other ions. Total N is weakly correlated with Sodium, Calcium and Magnesium in the WFM but not correlated with any ion in the Xeric West. Furthermore, total P and total N are not correlated in the WFM but loosely correlated in the Xeric West.

The strong correlation among cations and total P concentrations in the WFM are an indication that there is a natural total P gradient related to watershed geology/soils. In the XW, since total P is related to the monovalent group but not the divalent group, the total P source could be a specific geologic source that is only related to Potassium or Sodium or it could be associated with land use, e.g. fertilizers that are high in the monovalent cations. This latter interpretation is supported by the fact that total P and total N were correlated in the Xeric West but not in the Western Forested Mountains, i.e. due to exogenous inputs of both nutrients into these watersheds.

Table 5. Spearman correlation coefficient matrix for nutrient related variables in 24 reservoirs in the Western Forested Mountain ecoregion and 24 reservoirs in the Xeric West ecoregion. Correlations significant at $p<0.05$ are shown in bold, correlations significant at $p<0.001$ are starred (*).

WESTERN FORESTED MOUNTAINS								
Vari	TP	TN	Chl-a	Sec	Turb	Ext.	Abs3	DOC
TP	----							----
TN	0.6	----						**0.9**
Chl-	0.5	0.4	----					
Sec	-0.5	-0.5	-	----				
Turb	0.0	0.3	1.	0.0	----			
Ext.	0.5	0.6	0.7	-	0.7	----		
Abs	0.2	0.6	0.	-0.5	0.5	0.7	----	**0.8**
Abs	0.2	0.6	0.	-0.4	0.6	0.7	0.9	0.7

XERIC WEST								
Vari	TP	TN	Chl-a	Secch	Turb	Ext.	Abs3	DOC
TP	----							
TN	0.68*	----						
Chl-	0.60	0.55	----					
Secc	-0.86*	-	-0.55	----				
Turb	0.80*	0.49	0.48	-0.88*	----			
Ext.	0.84*	0.56	0.50	-0.89*	0.96*	----		
Abs3	0.73*	0.45	0.23	-0.80*	0.83*	0.83*	----	----
Abs4	0.68*	0.35	0.16	-0.77*	0.87*	0.85*	0.96*	----

TP = Total Phosphorus, TN = Total Nitrogen, Chl-a = Chlorophyll-a, Secchi = Secchi Depth, Turb = Turbidity,Ext. = Light Extinction Coefficient, Abs325 = Absorbence at 325 nm, Abs440 = Absorbence at 440 nm

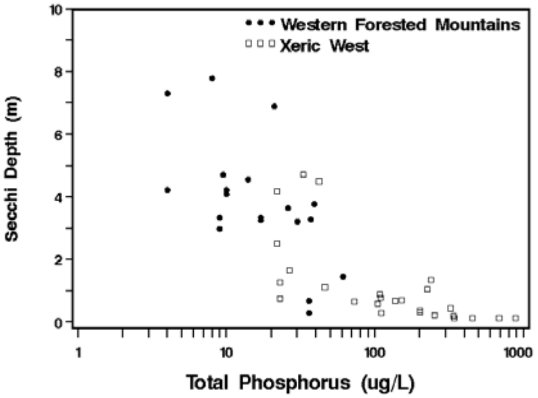

Figure 13. Relationship between Secchi depth and total phosphorus. Water transparency decreases with increasing total phosphorus.

Table 6. Spearman rank correlation coefficients among base cations, anions, total phosphorus (TP) and total nitrogen (TN) in 24 Xeric West and 24 Western Forested Mountain reservoirs. Bold values are significant at $p < 0.0001$. Values with significance below 0.1 are shown as n.s.

	K	Na	Ca	Mg	*SO_4*	CL	TP
				Western Forested Mountains			
K	-						
Na	**0.90**	-					
Ca	**0.72**	**0.73**	-				
Mg	0.77	0.86	**0.86**	-			
SO_4	**0.56**	**0.59**	**0.79**	**0.65**	-		
CL	**0.55**	**0.64**	**0.58**	**0.71**	**0.67**		
TP	**0.84**	**0.82**	**0.66**	**0.73**	*ns*	0.58	-
TN	*ns*	**0.53**	***0.57***	***0.66***	*ns*	*ns*	*ns*
				Xeric West			
K	-						
Na	**0.75**	-					
Ca	*ns*	**0.56**	-				
Mg	*ns*	**0.53**	**0.91**				
SO_4	*ns*	**0.63**	*0.76*	0.66	-		
CL	0.80	**0.89**	*ns*	*ns*	**0.65**	**-**	
TP	**0.61**	**0.48**	*ns*	*ns*	*ns*	*ns*	-
TN	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	**0.63**

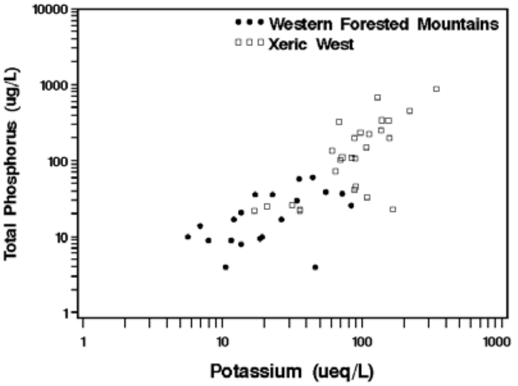

Figure 14. Scatter plot of total phosphorus versus potassium concentration in Pacific Northwest reservoirs. Total P has a higher correlation with Potassium in the WFM than the XW.

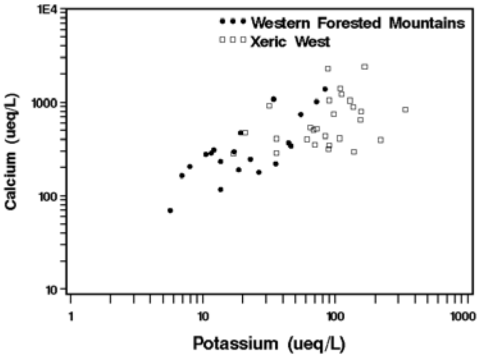

Figure 15. Scatter plot of total phosphorus versus potassium concentration in Pacific Northwest reservoirs. Calcium and Potassium are more highly correlated in the WFM than in the XW.

As the nutrient variables are highly correlated with each other, it's not necessary to consider how other variables relate to all of them. TP and chlorophyll-a were selected as nutrient indicator variables and analyzed to see how other reservoir variables related to them (Table 6). In examining the data it became apparent that the two ecoregions behaved differently so the results are presented separately for each ecoregion. In the Xeric West, no variables were highly correlated ($p < 0.001$) with either TP or chlorophyll-a. TP was significantly related ($p < .05$) to potassium, dissolved oxygen, shoreline disturbance, and maximum reservoir depth. In the Western Forested Mountains, many variables were significantly related to both TP and chlorophyll-a. Indicators of water ionic strength (base cations, alkalinity, conductivity were highly correlated with both nutrient variables. Reservoir surface area, depth below full pool, sulfate, redox potential, and shoreline ground cover w were not related to either nutrient variable in either ecoregion (Table 6).

Potassium was most strongly related to TP in both ecoregions (Fig. 15). The log-log plots have similar slopes in both ecoregions though the relationship is less variable in the Western Forested Mountains. On the other hand, calcium is strongly related to TP in the Western Forested Mountains but is not related to TP in the Xeric West. Plots of calcium versus potassium show that the two base cations are strongly related in the Western Forested Mountains (r=0.74) but unrelated \in the Xeric West (r=0.28; Fig. 15). In the Western Forested Mountains, all four base cations are correlated with each other with an r>0.75.

In the WFM DOC was strongly correlated with absorbence at both 325 and 440 nm (Table 5). In contrast there was no correlation among these variables in the Xeric West. Considering that median DOC was five times higher in the XW than in the WFM, the absence of a correlation between these parameters in the XW is problematic. This may have to do with the high turbidities in the XW, which were highly correlated with absorbence and thus masked any relationship to DOC.

Shoreline structure indices were not strongly correlated with any water chemistry variable in the data set. Although there appeared to be a rough negative correlation between total shoreline vegetation ground cover and total P concentrations, correlations were insignificant. This result has not been controlled for season, i.e. reservoir draw down.

Cluster Analysis

One of the objectives of this research was to develop classes or a typology for Pacific Northwest reservoirs to aid in developing nutrient criteria. Two approaches were tried; visual inspection of anion/cation chemical composition, and an overall cluster analysis. To investigate anion/cation composition, trilinear diagrams were used that show the relative % composition of various ions on a triangular plot. For both anions and base cations, there were no apparent clusters of lake types and this doesn't appear to be a useful approach for developing a reservoir typology

To develop clusters from the reservoir data for each Nutrient Ecoregion, a principal components analysis (PCA) was used to identify the major components in the data. These components or factor scores for each site were then clustered. Results of the PCA are very dependent on what variables are included. It's also desirable to have non-redundant variables. It was also desirable to select a set of variables that cover a range of reservoir characteristics that are not correlated with one another. Five variables were chosen for the PCA analysis for the Xeric West (Table 7). Potassium and alkalinity were selected to represent ionic strength. Both were used as they represent different processes in the Xeric West and were not correlated with each other. Water clarity was represented by three separate factors: Abs325, turbidity and chlorophyll.

The resulting PCA had 4 factors or axes that each explained more than 10% of the variance and these 4 site factor scores were used for the subsequent cluster analysis. All together, these 4 components explained 98% of the variance in the 5 variables. In looking at the correlation of the original 5 variables to the axis scores, axis 1 can be considered an ionic strength/transparency axis, axis 2 is related to alkalinity, axis 3 is related to chlorophyll, and axis 4 is a turbidity axis. We included chlorophyll as a variable in an attempt to separate algal and nonalgal turbidity.

From the cluster analysis of the four axes scores, four clusters were identified from the resulting dendrogram (Fig. 16). Box and whisker plots showing how the clusters differ on reservoir variables are useful in assigning cluster attributes .

Cluster 1 – Low ionic strength, high transparency, low absorbence, low turbidity.

Cluster 2 – Moderate ionic strength, moderate transparency, moderate absorbence, moderate turbidity due either to algae or particulate matter.

Cluster 3 – Moderate ionic strength, low transparency due to non-algal turbidity.

Cluster 4 - High ionic strength, very high absorbence, very low transparency due to algal and/or nonalgal turbidity.

We found no components for reservoirs in the WFM. The magnitude of total P in these reservoirs ranged from 4 to 61 ug/L (Appendix 1). Base cations and total P were all correlated in this Nutrient Ecoregion, suggesting that a common mechanism explains the concentrations of total P in these reservoirs (Table 6). The highest total P concentrations were found in reservoirs (e.g. Lake Simtustus, Toketee, Willow Creek) that have very high natural sources of phosphorus. Excluding these reservoirs, the other reservoirs in the WFM all had total P concentrations less that 40 ug/L. If there are significant differences among these

Table 7. Variables used in principal components analysis, their correlation with the four PCA axes, and the amount of variance explained by each PCA axis. Cumulatively, the four axes explained 98% of the variance in the 5 variables.

Variable	Axis 1	Axis 2	Axis 3	Axis 4
Potassium	0.52	0.31	0.18	-0.32
Alkalinity	0.03	0.89	0.20	0.15
Abs325	0.50	-0.28	0.45	-0.41
Turbidity	0.55	-0.15	0.05	0.81
Chlorophyll	0.41	0.11	-0.85	-0.20
% variance	58%	24%	14%	3%

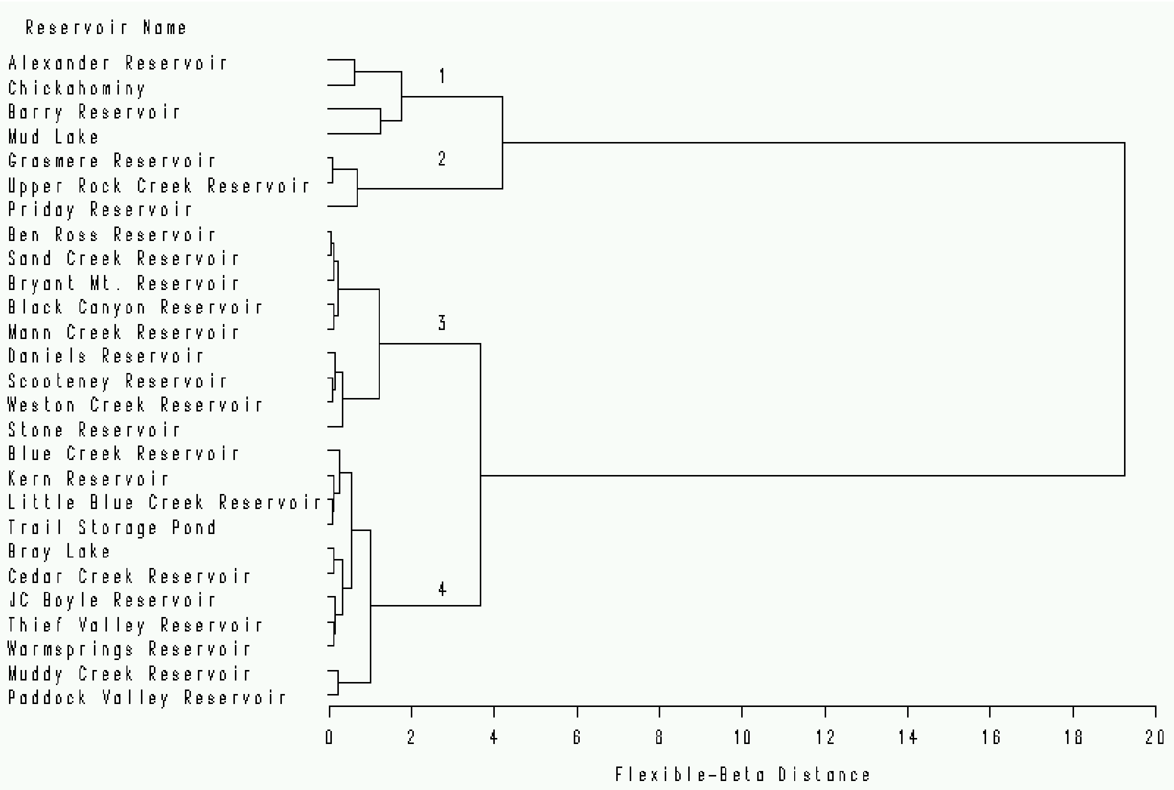

Figure 16. Dendrogram of the cluster analysis of the four PCA axes for the 27 reservoirs in the Xeric West showing the 4 cluster used in subsequent analysis.

reservoirs with respect to landscape, we weren't able to discern them with in our data set.

Reservoir Categories

Developing a typology or classes is an essential first step for developing nutrient criteria for reservoirs. Based on water quality data for each of the clusters described in section 5, we propose a reservoir typology for the Xeric West with three categories.

Category 1 – Low ionic strength, high transparency, low absorbence, low turbidity, low chlorophyll.

Category 2 – Moderate ionic strength, moderate transparency, moderate absorbence, moderate turbidity due either to algae or particulate matter.

Category 3 – High ionic strength, very high absorbence, very low transparency due to algal and/or nonalgal turbidity.

Categories 1 and 2 are the same as clusters 3 and 4, respectively. Category 3 is a combination of clusters 1 and 2 (Fig. 21).

Cutoff criteria for these types were selected to preserve the original clustering as much as possible. Thus, this typology preserves the segregation observed in the original clustering but has very simple parameters used to define the types. Reservoir typing could be done with a simple field visit and measurements of conductivity, turbidity, Secchi and chlorophyll. These measurements can all be made fairly inexpensively.

Characteristics of Reservoir Categories in the Xeric West

There was no apparent relationship between reservoir category and geographic location (Fig. 17). However, all but two of the reservoirs in the Xeric West (Scooteney in Columbia Basin and Thief Valley in Blue Mountains) were in the Level III Northern Basin and Range Ecoregion. Therefore if additional reservoirs are sampled in the Columbia Plateau this absence of apparent geographic effect may not hold. Conversely, classification of reservoirs by Nutrient Ecoregion may prove to be effective as an initial method to stratify reservoirs by location for purposes of developing nutrient criteria.

The three types of reservoir thus determined show differences in terms of total P, total N Secchi but not chlorophyll concentrations (Fig. 18-21).

For natural water bodies, once a typology has been established, nutrient criteria would be established by looking at the distribution of nutrient levels in a set of undisturbed of reference systems of a given category. That would provide a scientifically defensible picture of what natural nutrient concentrations ought to be for setting criteria. For reservoirs, however, there is no way to have natural reference sites. Reservoirs by their very nature are artificial human built systems so the reference site concept doesn't apply. Thus, setting nutrient criteria for reservoirs will be especially problematic.

One method to define nutrient criteria is based upon a percentile distribution of scores of all systems in each category (EPA, 2000). Recent data suggest that in the Pacific Northwest the median-75% interquartile is an appropriate range for total P values in lakes and reservoirs (Vaga and Herlihy 2004). Percentile scores and medians for nutrient criteria variables for each reservoir category are listed in Table 8. Using the percentile approach, total P nutrient criteria for Category 1 reservoirs would be <33 ug/L , <238 ug/L in Category 2 reservoirs and <686 ug/L in category 3 reservoirs. Similarly, criteria for Secchi depth would be 2.1, 0.70 and 0.15 meters, respectively. It is evident that the high variances of total N and chlorophyll preclude any determination regarding meaningful assignments of criteria using this method. Whether a larger sample size would provide more precise determinations of these parameters among reservoir categories is problematic. Category 1 reservoirs are clearly relatively oligotrophic compared with the other categories.

Chlorophyll values in Category 2 reservoirs indicate a variability based upon season but water transparency is sufficient to allow for development of significant algal biomass. Category 3 reservoirs evidently have the potential for significant accumulation of algal biomass but that potential can be limited by nonalgal turbidity. In this study we attempted to differentiate among the effects of color, absorbence, algal turbidity and nonalgal turbidity. It is evident that in Category 3 reservoirs we were unable to accomplish this differentiation due to the fact that we did not have data on Total Suspended Solids. In future studies it is imperative to collect Total Suspended Solids data to explicitly differentiate the effects between algal and nonalgal effects on water transparency. At all events, the results presented here provide a useful guide to future investigations regarding reservoir nutrient dynamics in the Pacific Northwest.

Discussion

The magnitude of the median values for total P, total N, Secchi and chlorophyll compare favorably with published values (Table 9). Total P values were roughly two times those reported earlier (Vaga and Herlihy 2004). This is reasonable, since Vaga & Herlihy included a preponderance of natural lakes versus reservoirs and thus their values would be expected to be lower than for reservoirs alone. A similar relationship exists for Secchi and chlorophyll, i.e. the reservoirs appear to be more eutrophic. Interestingly total N values reported here appear to be one-half of the lake+reservoir study cited above. These data suggest that reservoirs are relatively nitrogen poor as compared with natural lakes but the reason for this is unclear. However, these values for total P and total N suggest that natural lakes in the WFM and XW have N:P ratios of 38.7 and 13.2, respectively. In contrast reservoirs in the WFM and XW have ratios of 9.7 and 3.9, respectively. Thus irrespective of Nutrient Ecoregion, nutrient criteria for reservoirs may have to take total N into account.

Reservoirs typically are relatively nutrient rich during the first years after construction due to leaching of nutrients from the recently flooded soils (Thornton et al., 1990). Reservoir age did not appear to be a factor in this study. Reservoirs in the WFM were constructed between 1910 and 1989 (average age 56 years) and those in the XW between 1895 and 1970 (average age 64 years). In neither Nutrient Ecoregion were any water quality/nutrient parameters correlated with reservoir age, suggesting that any effects due to construction are no longer factors in the nutrient dynamics of these reservoirs.

Reservoirs tend to be long and narrow resulting in a gradients in physical, chemical and biological parameters from the upstream end to the dam. This gradient can be divided into three general zones, e.g. riverine, transition and lacustrine (Thornton, et al., 1990). Typically the transition zone exhibit the highest productivity and the lacustrine portion of reservoirs exhibit relatively low productivity, since nutrients are removed by algal settling in the transition zone. In this study we limited sampling to the lacustrine areas of the reservoirs and more specifically to the forebay. Thus our estimates of nutrient concentrations, Secchi and chlorophyll are only representative of the most nutrient poor region of the reservoirs. Other zones in these reservoirs would in all probability exhibit different nutrient dynamics.

In addition to sampling location, season also plays an important part in the be be expected to have higher nutrients and chlorophyll concentrations. nutrient dynamics of reservoirs. As in lakes, reservoirs often exhibit a spring bloom of phytoplankton followed by a clear water phase in midsummer and a secondary bloom in the fall (Wetzel 2001). In seven WFM reservoirs total P was ≤ 10 ug/L (Appendix 1, 2). These low levels are probably indicative of nutrient conditions in these reservoirs but without further study we cannot rule out the possibility of higher concentrations early in the year. The same holds for the six reservoirs in the XW with concentrations ≤ 30 ug/L.

In the Xeric West high chlorophyll concentrations were not always observed in the presence of high total P concentrations (Appendix 1, 2). For example, in Category 3 reservoirs Chickahominy and Alexander had over 600 ug/L of total P and chlorophyll above 400 ug/L (Fig. 11, Appendix 2). However, several reservoirs had over 100 ug/L of total P (e.g. Upper Rock, Priday, Barry, Grasmere, Warmsprings) but less than 10 ug/L of chlorophyll. In several cases the presence of nonalgal turbidity (Upper Rock) or absorbence due to DOC (e.g. Barry, Priday, Grasmere) may have prevented development of high algal biomass. However, we cannot discount the fact that we may have missed an algal bloom in these reservoirs.

Table 8. Median and 75th percentile (Q3) values for nutrient criteria variables in the three proposed nutrient criteria reservoir categories. n = number of reservoirs in category.

C	n	TP Med(Q3)	TN Med(Q3)	Chl-a Med(Q3)	Secchi Med(Q3)
1	9	25(33)	258(399)	2.1(4.6)	2.10(4.4)
2	11	137(238)	483(578)	27.9(76.9)	0.70(0.9)
3	7	344(686)	385(1930)	7.9(460.6)	0.15(0.3)

Table 9. Comparison of median (± 1 se) values for total P, total N, Secchi and chlorophyll observed in this study with those calculated from Vaga and Herlihy (2004) for lakes and reservoirs in corresponding Nutrient Ecoregions.

Variable/ Source	WFM		XW	
	Mean	se	Mean	se
TP (ug/L)				
This study	23.0	13.6	109.0	43.7
Vaga/Herl	11.3	2.4	62.5	14.4
TN (ug/L)				
This study	213.2	54.3	430.9	46.3
Vaga/Herl	437.5	63.6	825.0	156.4
Secchi (m)				
This study	3.4	0.5	0.7	0.3
Vaga/Herl	4.5	0.2	1.6	0.4
Chla (ug/L)				
This study	4.6	3.1	7.5	27.8
Vaga/Herl	2.0	0.5	4.0	1.8

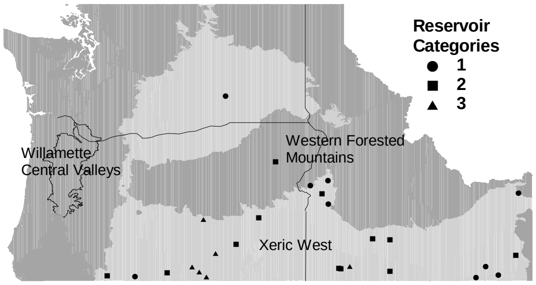

Figure 17. Location of the three reservoir categories in the Xeric West. There is no apparent relationship between category and geographic location.

The differences observed in reservoir total P and Secchi depth in the two different Nutrient Ecoregions reflects differences in landscape. Land use in the WFM is roughly 0, 12 and 80% agricultural, range land and forest, respectively. In the Great Basin and Range Ecoregion, where all but one of the XW reservoirs is located, land use is agricultural = 0, Range Land = 83 and Forest = 10%. These differences as well as differences in geology and weathering probably account for the observed differences in total P and Secchi depth. The high correlation of Potassium and total P in the WFM (Fig. 14, Table 6) suggests a single relatively homogenous source for phosphorus in these reservoirs, with relatively low effect of land use differences. The much weaker correlation observed in the XW is likely due to a more heterogeneous source. Whether this heterogeneity is due to land use e.g. fertilizers or geophysical processes, or a combination of both, is unknown.

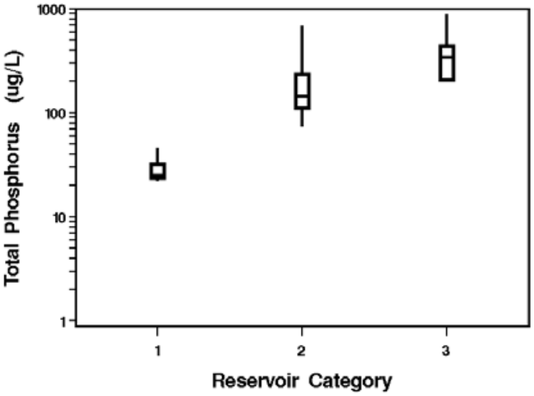

Figure 18. Distribution of total P values in the three reservoir categories in the Xeric West. There was a clear difference among the categories as defined by cluster analysis. Boxes show the interquartile range and median, whiskers the minimum/maximum values.

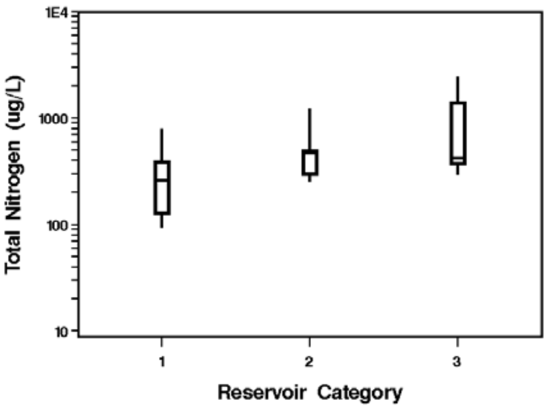

Figure 19. Distribution of total N values in the three reservoir categories in the Xeric West. Distributions of total N overlapped more than for total P among categories. Boxes show the interquartile range and median, whiskers the minimum/maximum values.

Conclusions

This study suggests that Nutrient Ecoregions are useful as an initial stratification variable for developing numeric nutrient criteria for reservoirs. There appears to be several lines of fruitful future investigation to further the development of nutrient criteria:

1) The minimum size of reservoir should be determined that will be subject to criteria. Small reservoirs, particularly in the Xeric West, are most likely to be subject to draw down during the summer to the level that makes criteria development unnecessary.

2) Conversely, the maximum size of reservoir should be determined where the relationship between measurable landscape parameters and nutrient concentrations in the reservoir can be empirically determined. For example, Columbia River reservoirs likely have no need for development of such criteria.

3) Greater resolution of nutrient dynamics in reservoirs in the Western Forested Mountains should be undertaken to ascertain to what extent these reservoirs can be considered as a single category. Such a determination may be made simply by accounting for local anomalies, e.g. high total P groundwater. It is also possible that reservoirs in the WFM are all similar enough to warrant placement into a single category.

4) Greater resolution of nutrient dynamics in reservoirs in the Xeric West should be undertaken to determine whether the three categories suggested in this study are sufficient to account for all reservoirs in this Ecoregion. In this study there was only one reservoir in the Columbia Plateau (Level III Ecoregion). Vaga and Herlihy (2004) found that lakes/reservoirs had a median and 75%percentile total P concentrations in the Columbia Plateau of 30 and 71 ug/L. In the Northern Basin and Range (Level III Ecoregion) similar values were reported and 90 and 204 ug/L. Thus it may not be appropriate to combine these two Level III Ecoregions into one population. In addition TSS rather than chlorophyll should be used in the classification process.

5) Downstream effects. The obvious high concentrations of total P in the Xeric West reservoirs should be evaluated with respect to tailwater effects on downstream habitats.

6) The value of N:P ratios, e.g. 3.9 N:P in the Xeric West, should be evaluated with respect to the need for nitrogen criteria and the concomitant effects on downstream systems.

7) Shoreline characteristics seem to be of less importance in determining nutrient concentrations than overall watershed characteristics. We surmise that at least for reservoirs that experience draw down, the effects of season are more important than shoreline characteristics at full pool.

Acknowledgments. We would like to thank Peter Leinenbach and George Gibson for reviewing an earlier draft of this report.

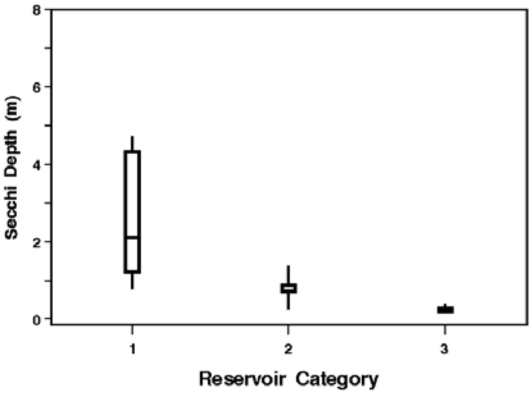

Figure 20. Distribution of Secchi depth in the three reservoir categories in the Xeric West. There was a clear difference among the categories as defined by cluster analysis. Boxes show the interquartile range and median, whiskers the minimum/maximum values.

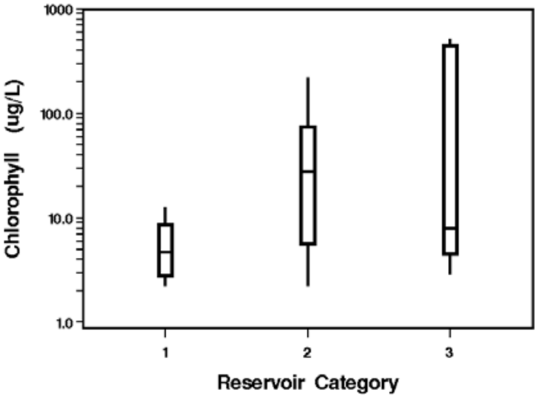

Figure 21. Distribution of chlorophyll values in the three reservoir categories in the Xeric West. The low variability in Category 1 reservoirs is due to relatively low nutrients. Category 2 reservoirs exhibit a higher median and variance due to seasonal effects, i.e. low nonalgal turbidity but higher total P. Category 3 reservoirs have low median but high potential for algal growth. Boxes show the interquartile range and median, whiskers the minimum/maximum values.

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Appendix 1. Nutrient and site data for Western Forested Mountain reservoirs.

NIDID	Lake Name	Latitud	Longitud	Chl-	Secc	Max	TP	TN
ID00337	Brundage	45.0418	116.1306	2.4	4.2	8.7	10	82
WA00263	Bumping Lake	46.8733	121.3000	0.1	7.8	11.0	8	
WA00264	Clear Lake	46.6333	121.2667	1.1	6.9	17.4	21	
WA00291	Conconully	48.5583	119.7450	7.5	3.7	6.8	26	279
WA00170	Diablo Lake	48.7133	121.1300	1.8	7.3	48.5	4	55
OR00016	Fern Ridge	44.1150	123.2917	36.9	0.3	6.5	36	182
OR00748	Galesville	42.8492	123.1778	5.7	4.1	31.7	10	116
OR10020	Henry Hagg	45.4917	123.2139	6.0	3.3	11.2	17	93
WA00183	Judy	48.4717	122.1883	1.3	3.0	6.8	9	192
OR00548	Lake Simtustus	44.6933	121.2300	34.8	1.5	42.0	61	164
OR83030	Laurence Lake	45.4583	121.6583	7.5	3.4	12.5	17	61
WA00223	Leader Lake	48.3617	119.6967	9.8	3.3	8.0	37	403
WA00021	Long Lake	47.8367	117.8383	3.5	5.2	16.7	110	864
WA00152	Mayfield	46.5033	122.5900	4.6	3.4	27.5	9	56
OR00550	N. Fork Clackamas	45.2417	122.2817	0.1	4.6	33.2	14	
OR00098	Ochoco	44.2983	120.7250	2.1	3.2	23.6	30	227
OR00579	Prineville	44.1133	120.7800	21.2	3.8	34.0	39	177
ID00115	Sage Hen	44.3255	116.1941	1.4	4.7	9.4	9.5	99
WA00153	Skookumchuck	46.7850	122.7167	2.8	4.2	29.5	440	173
OR00554	Toketee	43.2647	122.4194	0.4		7.6	58	58
OR00212	Willow Creek	42.4800	122.4433	18.8	0.7	7.9	36	167

NIDID = National Inventory of Dams ID code
Chl-a = Chlorophyll-a (µg/L)
Secchi = Secchi Depth (m)
Max Depth = Maximum Reservoir depth at time of sampling (m)
TP = Total Phosphorus (µg/L)
TN = Total Nitrogen (µg/L)

Appendix 2. Nutrient and site data for Xeric ecoregion reservoirs.

NIDID	**Reservoir Name**	**Latitude**	**Longitud**	**Chl-**	**Secc**	**Max**	**TP**	**TN**
ID00060	Alexander	42.6446	111.6960	519.	0.2	15.7	686	243
OR00108	Barry	42.0950	119.5317	2.9	0.2	4.0	344	385
ID00136	Ben Ross	44.5235	116.4446	2.2	2.5	12.0	22	118
ID00282	Black Canyon	43.9302	116.4357	2.6	4.2	21.0	22	93
ID00194	Blue Creek	42.3097	116.1807	2.2	0.9	5.8	108	509
ID00042	Bray Lake	43.0344	114.8760	76.8	0.7	2.8	137	371
OR00344	Bryant Mt.	42.1050	121.3283	10.2	0.8	1.1	23	598
ID00045	Cedar Creek	42.2237	114.8786	64.0	0.7	7.8	151	468
OR00228	Chickahominy	43.5450	119.6133	460.	0.2	3.6	887	193
ID00006	Daniels	42.3455	112.4424	4.8	4.5	9.8	42	258
ID00190	Grasmere	42.3555	115.9039	4.4	0.3	5.0	201	367
OR00559	JC Boyle	42.1231	122.0439	58.3	0.2	8.9	252	123
OR00181	Kern	42.9183	118.7817	27.9	0.7	5.8	73	274
ID00193	Little Blue Creek	42.2917	116.1203	18.8	0.8	6.3	109	292
ID00285	Mann Creek	44.3918	116.8928	7.5	1.7	14.4	26.5	123
OR00569	Mud Lake	42.2117	119.7150	29.3	0.2	2.7	456	453
OR00377	Muddy Creek	42.1950	120.5200	176.	0.5	6.4	325	579
ID00250	Paddock Valley	44.1983	116.5980	222.	0.3	4.5	110	929
OR00369	Priday	42.3400	119.9000	4.9	0.4	3.8	201	365
ID00010	Sand Creek	44.2025	111.6144	0.9		2.9	25	268
WA00566	Scooteney	46.6667	119.0333	12.7	1.1	11.0	46	792
ID00007	Stone	42.0680	112.6942	4.6	1.3	6.7	23	151
OR00592	Thief Valley	45.0150	117.7783	14.8	1.1	9.1	225	483
ID00239	Trail Storage Pond	43.0553	115.3196	5.5	0.6	6.0	104	514
OR00157	Upper Rock Creek	42.6867	119.3050	7.9	0.2	3.7	340	289
OR00082	Warmsprings	43.5850	118.2083	4.4	1.4	11.3	238	251
ID00074	Weston Creek	42.1302	112.1260	2.8	4.7	4.7	33	399

NIDID = National Inventory of Dams ID code
Chl-a = Chlorophyll-a (µg/L)
Secchi = Secchi Depth (m)
Max Depth = Maximum Reservoir depth at time of sampling (m)
TP = Total Phosphorus (µg/L)
TN = Total Nitrogen (µg/L)