Lake Water Quality and Health: Land Use Considerations for Small Lake Watersheds in King County, Washington

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Abstract

Urbanization and residential sprawl are raising concerns of the effects of land use and development on lake health and water quality. The Seattle region of the Puget Sound lowlands has experienced rapid growth, and hosts a large number of small lakes. This study conducted a land use analysis within 80 small lake watersheds in King County, Washington, U.S.A.

Water quality data (Secchi depth, Chlorophyll-a concentration, total phosphorus concentration) were obtained for these lakes. A variety of other data were also obtained, including: hydraulic retention time; whether the watershed relies upon sewer or septic systems for wastewater treatment; land uses within lakeshore and riparian buffers in the watersheds; development density along lakeshores; and average lake depth.

A large proportion of high density development within watersheds surprisingly was correlated to improved water quality, and a large proportion of low density and forested land uses were correlated to degraded water quality. In addition, watersheds that relied on sewer systems were found to have better water quality than watersheds that relied on septic systems. Longer hydraulic retention time was also correlated with improved water quality.

The results suggest several mechanisms that could be affecting water quality. Surface water management and drainage plans, which are implemented in areas of high density development, could be succeeding in protecting surface water quality. The morphology and nature of the lakes play a large role in water quality. In general, the results of this study suggest that a variety of processes affect water quality in lakes, and the complex and interwoven processes are not easily described by general relationships or simplified hypotheses.

Introduction

Urbanization has rapidly been increasing over the past 50 years in the Puget Sound lowlands (1). In this same time frame, interests in ecology and human impacts on the environment have also intensified. In King County, Washington (County), population grew by 230,000 people between 1990 and 2000, and is projected to grow by 300,000 additional people by 2010 (1). Areas that previously were rural and low density have grown into communities; areas previously undeveloped now host homes and neighborhoods. Throughout this growth, agricultural usage of land in the county has persisted, as have many private and public forestlands. The collective effects of these land uses on surface water bodies are of interest to planners and community members looking to improve and maintain aquatic health.

Land uses are known to have a variety of both positive and negative effects on lake health and quality. Urban activities and agriculture are major sources of phosphorus and nitrogen to water bodies. Eutrophication of surface waters—caused by excessive inputs of nitrogen and phosphorus—is the leading impairment of lakes (2). Urbanization, however, brings with it additional infrastructure and surface water management regulations that may mitigate the effects of urbanization. As urbanization intensifies, communities install sewer systems and retire septic systems. Septic systems are known to be a nonpoint source of nutrients (3), making the effects if urbanization on lakes and surface waters complex.

Relationships between land use and lake health are difficult to quantify. The purpose of this study is to test the relationships between lake health and land uses, as well to examine other mechanisms that might have significant impacts on lake health. The metrics of analysis were lake Secchi depth, chlorophyll-a (Chl-a) concentration, and total phosphorus (TP) concentration. The following hypotheses were tested in this study:
H_1. A large proportion of high density land uses in the watershed negatively impact lake health and quality.
H_2. A large proportion of forested land uses in the watershed positively impact lake health and quality.
H_3. Septic systems have a negative impact on lake health and quality.

Materials and Methods

Study Sites
King County, Washington is located in the Puget Sound Region of the Pacific Northwest. The County is home to almost 2 million people and experienced a 15% population growth from 1990 to 2000. The Seattle region is the most urbanized area in the Pacific Northwest (1). As the region develops, sprawl is reaching further east in the County, and up into the Cascade foothills. Development around many lakes and streams in eastern King County is becoming increasingly intense.

King County is home to more than 700 lakes that range in size from just a few acres to over 22,000 acres. The western third of the County hosts over 80 small lakes that measure less than 300 acres in size (4). Most small King County lakes are warm monomictic; however, there are a few examples of polymictic lakes in the area. The lakes are integrated into the urban and rural sprawl of the region. Few lakes have remained in a natural and undeveloped state, but more often the shorelines and watersheds accommodate housing developments, agriculture, and other activities.

The Puget Sound regional geology is dominated by prehistoric glaciations which reached a maximum approximately 15,000 years before present (YPB). The most recent ice-sheet advance into the region was the Vashon stade. The present topography of the region is a direct result of, or a strong imprint of, this glaciation. The majority of the lakes in King County are situated within stream systems on outwash deposits. The outwash is well-sorted, permeable sand and gravel. Conversely, some lakes are set upon the topographical plateaus of the area, which are often underlain by glacial till (5).

Aerial Photography
All aerial photographs and GIS information were analyzed using Arcview 3.3 (Environmental Systems Research Institute, Redland, CA). King County maintains extensive GIS data pertaining to surface water, public works projects, and other spatial information. Spatial delineations of small lake watersheds in the County were obtained from this database. Aerial photography from 1996 and 2002 were also obtained from King County. The standard projection for all King County GIS data (aerials and spatial layers) is State Plane, zone 5601, a HGPN datum, and in units of feet. An additional set of 1990 aerial photographs was obtained from the Washington State Geospatial Data Archive, maintained by the University of Washington. This set of aerials was developed by

the U.S. Geologic Survey and the U.S. Forest Service in the NAD83 datum. The 1990 aerial photos were projected to match King County's HGPN datum. In total, 3 sets of aerial photographs that cover King County in 1990, 1996, and 2002[1] were obtained, although there are many instances of deficient coverage of specific watersheds.

Land Use Delineations
Four classifications of land use were used to describe each watershed. These include cleared land, forested land, low density development, and high density development (Table 1). When developing these land use classifications, an attempt was made to group land use types with similar hydrologic dynamics. For example, golf courses, agriculture, cleared grassland and clear-cut forests were grouped under the assumption of similar evapotranspiration, storage, runoff, nutrient leaching, and soil stability.

Table 1. Land use classifications and examples

Classification	Criteria and Examples
Cleared	Golf courses, agriculture, grass, clear-cut forest
High Density	High density development (≥ 2 dwelling units per acre)
Low Density	Rural and low density development (< 2 dwelling units per acre)
Forested	Forest, dense vegetation that would replicate forested evapotranspiration

Criteria were also developed to determine if a plot of land of a particular land use was large enough to delineate. In general, if a particular land use occupied more than 10 acres of land, it was delineated as that land use. Near lakeshores, a smaller standard was used, assuming that land use activities nearer the lakeshore have a more significant impact than land use activities at the far reaches of the watershed. The majority of lakes in the study area have some degree of development along the lakeshore. Therefore, the majority of lakes in the study area have a road circumnavigating the lakeshore with just one waterfront parcel to the inside of the road. If a particular land use occupied more than 1 acre of land inside this road, or 1 acre of land adjacent to the lakeshore, it was delineated as that specific land use.

The delineations were completed by visually examining the aerial photography in Arcview 3.3 software, then drawing a polygon around the specified land use on the aerial. This was done so that the entire watershed was classified as a patchwork of the various land uses. Instances occurred where it was difficult to determine a land use from the aerial photograph, for reasons of shadows from clouds and hillsides, obstruction of the photograph by cloud cover, or simply the land use was indistinguishable. In these cases, further investigation was necessary. Parcel information maintained by the County was examined, as well as occasionally visiting the site or pursuing other research avenues.

This process of land use delineations provided the following information: total watershed area, total area of each classified land use within the watershed, total area of the lake itself, and shoreline length.

Other GIS Information
Spatial GIS information was obtained from King County that includes the locations of surface water streams that flow into lakes in the study area. This GIS data was overlaid on the watershed delineation and lake location. The streams were clipped at the watershed boundary, and streams that did not flow into the lake were eliminated. A 150 foot buffer was determined along each

[1] One lake watershed (Margaret) was only covered by half of the King County 2002 aerial. The northern half lies in Snohomish County. This portion was covered by a 2001 Snohomish County aerial. These two portions were put together to summarize land use in 2001-2002.

stream and lakeshore. The land uses within these buffers was calculated to examine the relationship between land use within the lakeshore and riparian buffer and lake water quality.

Sewer information was obtained from the King County GIS database. This data was a delineation of County sewer areas. This GIS layer was created by the County with a similar objective as was desired for this study—to identify sewered and unsewered areas—and was originally used in a hydrologic model. The sewer GIS layer was overlain with the watershed delineations. If the watershed existed within a sewered area, it was categorized as sewer. Otherwise, it was categorized as septic. All watersheds except two were entirely within or outside sewer districts. These two watersheds were partially within a sewer district. The watersheds were visually assessed to determine if it was more appropriate to classified them as sewer or septic. In both instances, the portions of the watershed on sewer covered all high density development and the majority of low density development. For this reason, they were both classified as sewer. To test the accuracy of the sewer district GIS information, shoreline parcels were sampled on 3 lakes to compare parcel information to the sewer districts. The test on parcel information supported the assumption that the sewer GIS information was a useful indicator of whether a watershed was on sewer or septic systems.

Water Quality Data

The Metropolitan Municipality of Seattle (METRO) initiated a volunteer program of sampling King County lakes in 1984. This program sampled 51 small lakes in King County. In 1995, the METRO program was merged with the King County Lake Stewardship Program, increasing the number of monitored lakes by eighteen. In 2000, seven additional lakes were added to the program (4). Lake volunteers were predominantly lakeshore residents. Training for the volunteers was conducted by Lake Stewardship Program staff, and the volunteers are provided a sampling protocol manual, Secchi disk, Van Dorn sampling bottle, sample containers, and other equipment. Lake water samples were taken every two weeks from May through October. The samples were taken at one meter depth while the volunteer was anchored at a specified position in the lake, generally over the deepest point (6). The samples and data sheets were collected by King County staff, and the samples were sent to a King County laboratory to be tested for total phosphorus (TP), Chlorophyll-a (Chl-a), and, since 1997, total nitrogen.

For the purpose of this study, seasonal and annual water quality data were averaged to remove bias due to individual lake trophic dynamics or interannual variability. A May-October average Secchi depth, TP concentration, and Chl-a concentration were determined for the sampling season (May-October) for each lake. These averages were obtained for each year that an aerial photograph is available (1990, 1996, and 2002), as well as the year preceding and following these years (1989 and 1991, 1995 and 1997, 2001 and 2003. To remove interannual variability and to make the water quality parameters comparable across years, three annual averages (i.e. 1989, 1990, 1991) were averaged to determine the 1990, 1996, and 2002 average values of the water quality parameters for each lake. These averaged values were used in this study.

In 1997 the King County Environmental Lab changed their procedure for determining TP. Prior to 1997 the laboratory used a single digestion technique to isolate phosphorus. Since 1997, a double digestion technique has been used to isolate both TN and TP from a water sample. This change in techniques resulted in a subtle systematic bias of TP values in the laboratory results. King County statisticians have determined a mathematical function that back-transforms TP values collected post-1997 (TP_{new}) to pre-1997 (TP_{old}) values. This transformation function is described below:

$$TP_{old} = e \text{ ^ } [0.411 + 0.952(LN\ TP_{new})]$$

Using this method, pre-1997 values remained as TP_{old}; values from 1997 and after were converted to TP_{old} values using the above transform function. This transform function allowed TP values from 1990 through 2002 to be comparable, and all TP_{old} values will hereafter be referred to as TP.

Statistical Data Analysis
A statistical software package, SPSS 12.0 (SPSS, Incorporated, Chicago, IL), was used for all statistical procedures. The water quality distributions, as well as the HRT distribution, did not demonstrate normality. The water quality parameters (Secchi, Chl-a, TP), as well as HRT values, were $\log_{10}$ transformed. All analyses were performed on transformed values. Log_{10} transformed water quality parameters ($\log_{10}$ Secchi, $\log_{10}$ Chl-a, and $\log_{10}$ TP) and percent watershed land use were analyzed using Pearson's correlation to demonstrate possible relationships between land use and water quality. In addition, a variety of other lake characteristics (hydraulic retention time (HRT), mean lake depth, total watershed area, total area of specific land use, and the number of parcels per 1000 feet of lakeshore) were correlated to $\log_{10}$ transformed water quality parameters to demonstrate further possibilities for relationships with and drivers of water quality.

A backward elimination multiple regression was performed to determine the strongest drivers of water quality in lakes, examining those drivers that demonstrated significance in the Pearson correlations with water quality (7).

Results

Land Use Results
Table 2 summarizes the results of the land use analysis. The sample includes 18 lakes with land use delineations for all three (1990, 1996, 2002) years. The sample includes 46 lakes for two of the three years, and the sample includes 16 lakes with a single year's aerial delineated for land use. In total, there are 80 distinct (n = 80) snapshots of land use in King County lakes with corresponding water quality data.

Table 2. Summary of land use within watersheds (total acreage and percentage)

	(acres)	**(percentage)**
Total Watershed Area		
Mean ± Standard Deviation	744 ± 1355	
Median	351	
Min — Max	64 — 7848	
High Density Land Use		
Mean ± Standard Deviation	89 ± 119	21 ± 27
Median	23	9
Min — Max	0 — 512	0 — 97
Low Density Land Use		
Mean ± Standard Deviation	226 ± 385	35 ± 22
Median	100	35
Min — Max	0 — 2066	0 — 90
Cleared Land Use		
Mean ± Standard Deviation	136 ± 372	14 ± 13
Median	43	11
Min — Max	0 — 2641	0 — 100
Forested Land Use		
Mean ± Standard Deviation	293 ± 688	30 ± 27
Median	78	28
Min — Max	0 — 4457	0 — 100

As indicated in the table above, the watersheds ranged in size from 64 acres to 7848 acres. The mean size watershed was 744 acres, and the median size of watershed was 351 acres, indicating that the majority of the watersheds are small. The range of land uses within these watersheds

covered a large range as well and most watersheds contained some amount of each of the four land uses. This allows the study to look at a wide variety of land use effects in watersheds.

Water Quality Parameters

Initially, the water quality parameters were examined to ensure that the data follows general trends postulated by lake dynamics theory. These assumptions were: Secchi depth decreases as concentrations of Chl-a or TP increase, and Chl-a concentrations increase as TP concentrations increase. This analysis entailed correlating Secchi depth to Chl-a and TP, and correlating TP to Chl-a. Figure 1 indicates the results of this correlation.

Figure 1. Water quality parameters results

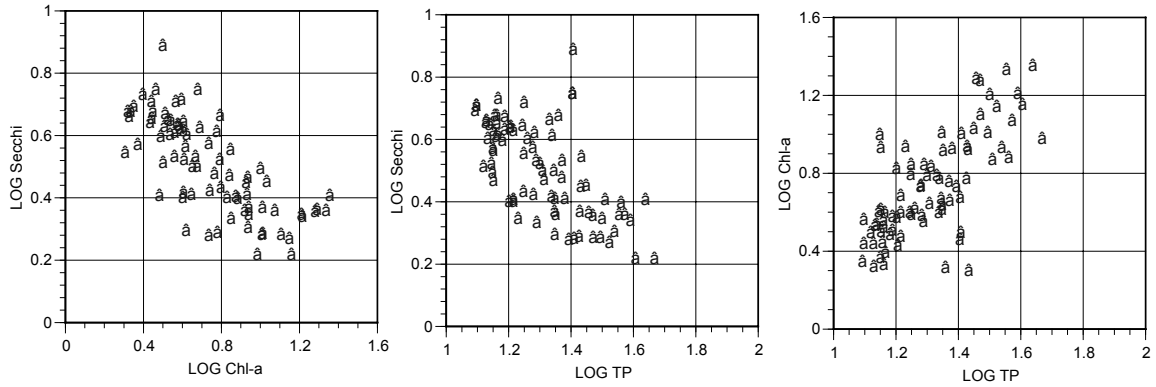


Table 3. Summary of water quality parameter results

	log_{10} Chl-a vs. log_{10} Secchi	log_{10} TP vs. log_{10} Secchi	log_{10} TP vs. log_{10} Chl-a
r	0.668	0.677	0.724
r^2	0.446	0.459	0.524
F	82.883	66.101	84.742
P	< 0.05**	< 0.05**	< 0.05**
N	80	80	80
Fit	Power	Power	Power

** denotes significant results

Figure 1 and Table 3 indicates that the relationships amongst the water quality parameters demonstrate significant correlations. In other words, log_{10} Chl-a is negatively correlated with log_{10} Secchi depth ($r = 0.446$, $n = 80$, $p < 0.05$), log_{10} TP is negatively correlated with log_{10} Secchi depth ($r = 0.677$, $n = 80$, $p < 0.05$), and log_{10} TP is positively correlated with log_{10} Chl-a ($r = 0.724$, $n = 80$, $p < 0.05$).

Water Quality and Land Use Results

Land use was correlated with the 3 water quality parameters using a Pearson correlation. Scatter plots of the data are demonstrated in Figures 2, 3, 4, and 5 and the Pearson correlation results are summarized below in Tables 4, 5, 6, and 7.

Figure 2. Percentage of high density land use and water quality parameters

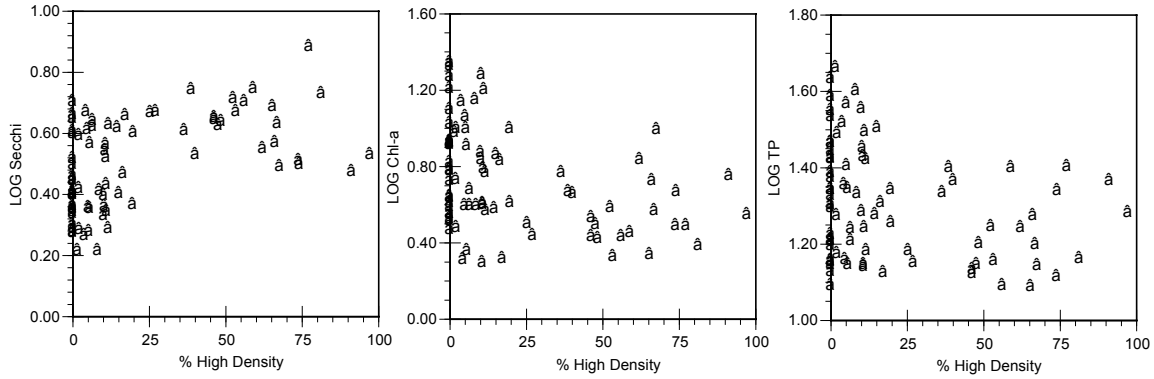


Table 4. Summary of percent high density land use and water quality parameter results

	% High Density vs. $\log_{10}$ Secchi	% High Density vs. $\log_{10}$ Chl-a	% High Density vs. $\log_{10}$ TP
r	0.509	0.405	0.296
r²	0.260	0.164	0.088
F	27.335	15.332	7.512
P	< 0.05**	< 0.05**	< 0.05**
N	80	80	80
Fit	Linear	Linear	Linear

** denotes significant results

Figure 2 and Table 4 indicate that percentage of high density development is significantly correlated with all three water quality parameters ($\log_{10}$ Secchi, $\log_{10}$ Chl-a, and $\log_{10}$ TP). Percentage of high density land use was positively correlated with $\log_{10}$ Secchi, and negatively correlated with both $\log_{10}$ Chl-a and $\log_{10}$ TP.

Figure 3. Percentage of forested land use and water quality parameters

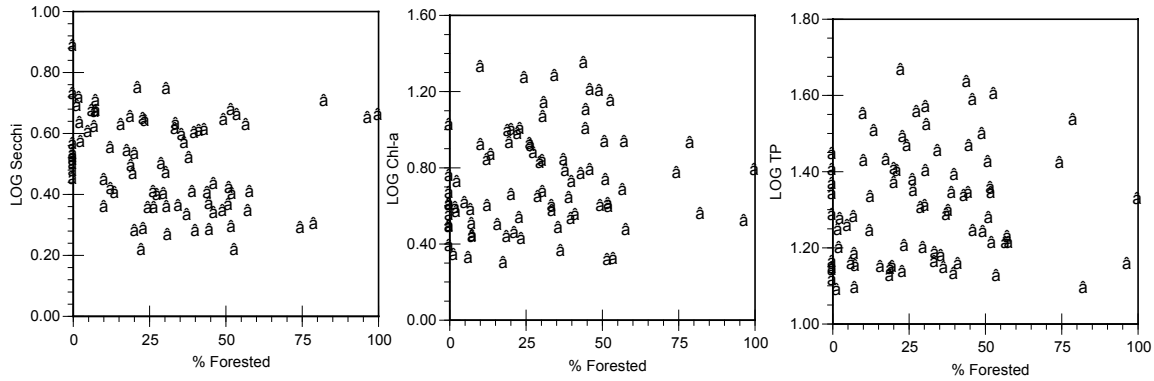


Table 5. Summary of percent forested land use and water quality parameter results

	% Forested vs. $\log_{10}$ Secchi	% Forested vs. $\log_{10}$ Chl-a	% Forested vs. $\log_{10}$ TP
r	0.335	0.251	0.202
r²	0.112	0.063	0.041
F	9.8827	5.229	3.309
p	< 0.05**	< 0.05**	0.073
n	80	80	80
Fit	Linear	Linear	Linear

** denotes significant results

Figure 3 and Table 5 indicate that percentage of forested land is significantly correlated with $\log_{10}$ Secchi and $\log_{10}$ Chl-a. The results for the correlation with $\log_{10}$ TP are slightly outside of the significance level of 0.05. Percentage of forested land use is negatively correlated with $\log_{10}$ Secchi, and positively correlated with both $\log_{10}$ Chl-a.

Figure 4. Percentage of cleared land use and water quality parameters

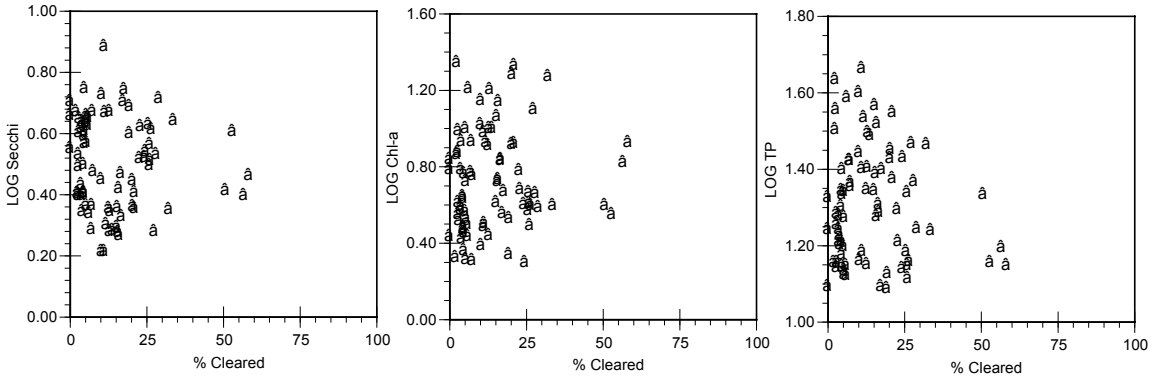


Table 6. Summary of percent cleared land use and water quality parameter results

	% Cleared vs. $\log_{10}$ Secchi	% Cleared vs. $\log_{10}$ Chl-a	% Cleared vs. $\log_{10}$ TP
r	0.155	0.120	0.038
r²	0.024	0.014	0.001
F	1.912	1.134	0.110
p	0.171	0.290	0.741
n	80	80	80
Fit	Linear	Linear	Linear

Figure 4 and Table 6 indicate that percentage of cleared land is not significantly correlated with any of the three water quality parameters.

Figure 5. Percentage of low density land use and water quality parameters

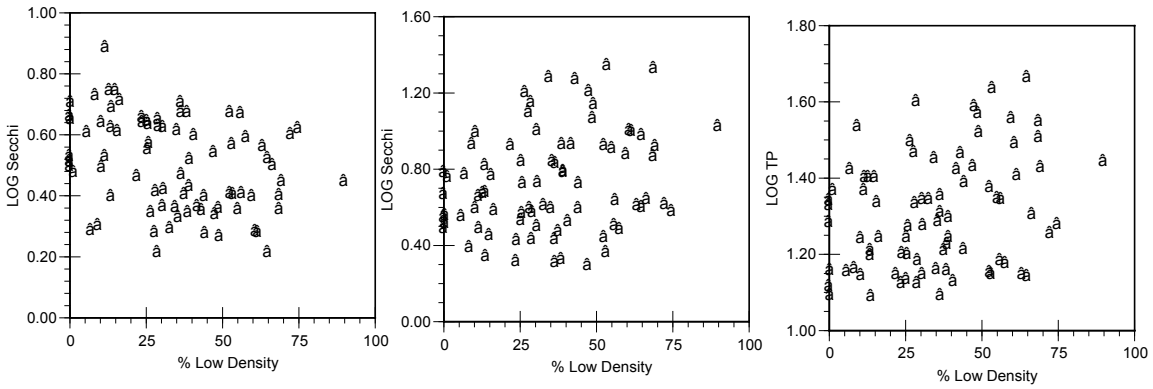


Table 7. Summary of percent low density land use and water quality parameter results

	% Low Density vs. log_{10} Secchi	% Low Density vs. log_{10} Chl-a	% Low Density vs. log_{10} TP
r	0.301	0.225	0.250
r²	0.091	0.051	0.063
F	7.794	4.162	5.222
p	<0.05**	<0.05**	<0.05**
n	80	80	80
Fit	Linear	Linear	Linear

** denotes significant results

Figure 5 and Table 7 indicate that percentage of low density development land is significantly correlated with all three water quality parameters (log_{10} Secchi, log_{10} Chl-a, and log_{10} TP). Percentage of low density land use was slightly negatively correlated with log_{10} Secchi, and positively correlated with both log_{10} Chl-a and log_{10} TP.

In addition to examining percent land use in comparison to water quality, raw values of land use acreage were also examined in comparison to water quality. This analysis did not yield significant results. Total watershed area was also examined. There was no significant correlation between total land use area and water quality.

Water Quality and Other Parameters Results

In addition to examining the effects of land use on lake water quality, other parameters were examined to see if there are other factors that affect water quality. These examined parameters include: whether the watershed uses sewer systems or septic systems for wastewater treatment; HRT of the lakes; types of land use within a 150 foot buffer of lakeshores and tributary streams that flow into lakes; density of parcels along lakeshores; and mean depth of the lakes.

In the interest of time and space, only those parameters that were significantly correlated with water quality are presented. These are HRT and whether the watershed was on sewer or septic systems. The other parameters (types of land use within a 150 foot buffer of lakeshores and tributary streams that flow into lakes; density of parcels along lakeshores; and mean depth of the lakes) demonstrated no significant trend with the water quality in a lake.

Figure 6. HRT and water quality parameters

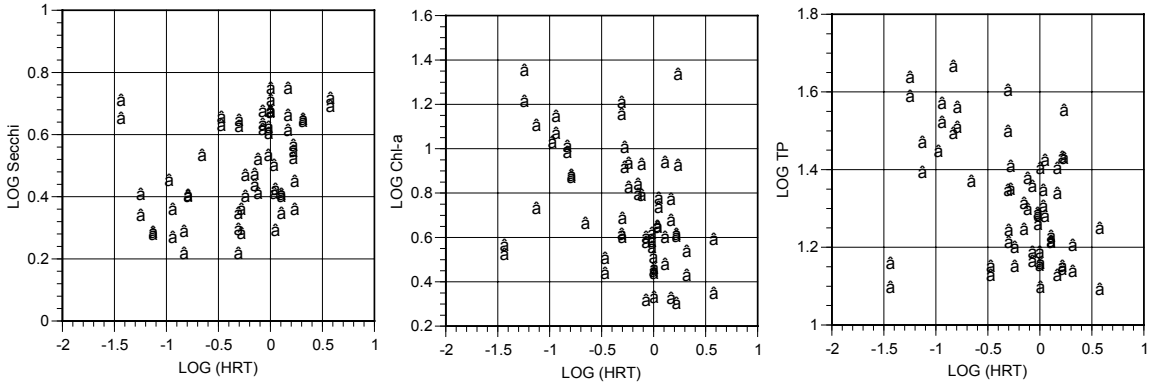


Table 8. Summary of hydraulic retention time and water quality parameter results

	log_{10} HRT vs. log_{10} Secchi	log_{10} HRT vs. log_{10} Chl-a	log_{10} HRT vs. log_{10} TP
r	0.376	0.460	0.431
r^2	0.141	0.212	0.186
F	9.387	15.325	13.023
p	< 0.05**	< 0.05**	< 0.05**
n	59	59	59
Fit	Linear	Linear	Linear

** denotes significant results

Figure 6 and Table 8 indicate that the log_{10} HRT value is significantly correlated with all three water quality parameters (log_{10} Secchi, log_{10} Chl-a, and log_{10} TP). HRT was positively correlated with log_{10} Secchi, and negatively correlated with both log_{10} Chl-a and log_{10} TP.

Figure 7. Sewer and septic lakes and water quality parameters

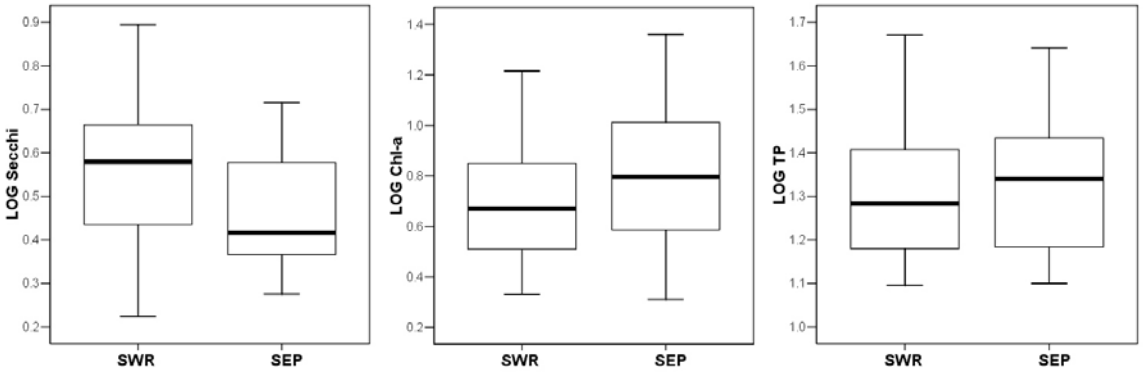


Table 9. Summary of sewer and septic lakes and water quality parameter results

	Sewer or Septic vs. log_{10} Secchi	Sewer or Septic vs. log_{10} Chl-a	Sewer or Septic vs. log_{10} TP
r	0.265	0.227	0.070
r^2	0.070	0.052	0.005
F	5.869	4.250	0.387
p	< 0.05**	< 0.05**	0.536
n	80	80	80
Fit	Linear	Linear	Linear

** denotes significant results

Figure 7 and Table 9 indicate that whether a watershed uses a sewer system or septic systems for wastewater treatment is significantly correlated with log_{10} Secchi and log_{10} Chl-a, but not with log_{10} TP. Watersheds that use sewer systems for wastewater treatment have larger Secchi depths and lower concentrations of Chl-a. Watersheds that use septic systems for wastewater treatment have lower Secchi depths and higher concentrations of Chl-a.

Multiple Regression Results

The backward elimination multiple regressions were performed using parameters that demonstrated a significant correlation with water quality. For Secchi depth and Chl-a, these were: percent high density; percent forested; percent low density; HRT; and sewer-septic. For TP, these were: percent high density; percent low density; and HRT. The results of this multiple regression are summarized below in Table 10.

It is important to point out that if two variables are highly correlated with each other, then only one will end up in the multiple regression analysis. Percent high density and sewer-septic were tested for correlation. There was a significant correlation between these two variables ($r = 0.615$, $n = 80$, $p < 0.05$). The multiple regressions for Secchi depth and Chl-a were conducted three times: once with both percent high density and sewer-septic included, and once each with one of the two variables excluded. The sewer-septic variable was not found to be significant even when percent high density was excluded. Therefore, the overall results of the multiple regression are summarized below.

Table 10. Summary of multiple regressions

Dependent Variables	**log_{10} Secchi**		**log_{10} Chl-a**		**log_{10} TP**	
R		0.61		0.58		0.50
R^2		0.37		0.34		0.25
Coefficient		***t-value***		***t-value***		***t-value***
Constant		16.333		12.750		28.710
Predictor I	HRT	4.136	% High Density	-3.643	% Low Density	2.720
Predictor II	% High Density	1.774	% Forested	-1.767	HRT	-2.969
Predictor III	-	-	HRT	-2.287	-	-

Use probability of F greater than or equal to 0.1 for removal of the independent variables from the multiple regression. Coefficients are significantly different from zero at a 0.05 significance level.

The multiple regression indicates that for Secchi depth, HRT and percent high density are the strongest drivers. Both of these drivers are positively correlated to Secchi depth. For Chl-a, percent high density, percent forested, and HRT are the strongest drivers. These three drivers are negatively correlated to Chl-a concentrations. For TP, percent low density and HRT are the strongest drivers. Percent low density is negatively correlated to TP concentration, while HRT is positively correlated to TP concentration.

The multiple regression was tested again, but this time only including lakes which contained less than 20% high density development. This was done to remove the highly developed lakes from the analysis and to look more closely at the relationship between development and water quality. However, because percent high density was highly correlated with sewer-septic ($r = 0.425$, $n = 56$, $p < 0.05$), the resulting multiple regression results excluded both percent high density and sewer-septic. The multiple regression suggested that HRT, percent forested, and percent low density had the greatest impact on water quality parameters.

Discussion

High density development is often assumed to be the driver of surface water degradation. The results of this study, however, indicate otherwise. This study failed to support the first hypothesis (H_1). Increased high density development was correlated with improved water quality. This was demonstrated with increased Secchi depth and decreased concentrations of Chl-a and TP as the proportion of high density development increases.

A potential explanation for this might lie in the associated processes that accompany high density development. This study demonstrated a high correlation between high density development and sewer installation within watersheds. Other associated processes might include master drainage plans leading to stormwater management, combined sewer overflow (CSO) management, and numerous other indirectly affected processes. For example, in 1985 the state of Washington enacted the Washington State Water Pollution Control Act (RCW 90.48) which required that all municipalities with CSOs develop a plan for "…the greatest possible reduction at the earliest possible date" (8). As the Seattle-region has grown and new sewer districts come online, there is increased control of CSOs, aiding in pollution control of surface waters, despite increasing

development. It is perhaps the placement of such infrastructures and policies and implementation of protective policies that leads to improved water quality despite increased development.

Although counterintuitive, this study found that forested and low density development land uses are correlated with degraded water quality. It is perhaps a lack of infrastructure that accompanies high density development that leads to degraded lake water quality. In Figure 3, the correlations between percent forested and water quality is demonstrated in a scatter plot. The statistical analysis failed to support the second hypothesis (H_2). While the results for the correlation between increased forested land use are significantly and negatively correlated with Secchi depth, and significantly and positively correlated with increased Chl-a and TP concentrations, it is important to look at 3 specific watersheds in those figures. These three watersheds are nearly or completely undeveloped (> 80% forested). They maintain relatively high Secchi depth and low concentration of Chl-a and TP, converse to the prevailing trends exhibited by other forested land use. It is the gradient of forested land use between 0-80% that visually exhibits the trend of degraded water quality. Again, perhaps it is the encroachment of low density development, lacking in mitigating infrastructures and policies, which lends it to water quality degradation.

An infrastructure process that is related to water quality is demonstrated in this study. If a watershed relies on septic systems for wastewater treatment, the lakes tend to have lower Secchi depths and higher concentrations of Chl-a and TP. These results support the third hypothesis (H_3). Furthermore, these findings are in agreement with the conclusions of Moore, et al. (9), and are based upon a rigorous lake sampling routine and extensive collection of lakes in the region. By design, septic tanks slowly release nutrients into the surrounding soils. Many of the lakes in King County are located in highly permeable soils, allowing nutrients be easily transported through groundwater and into surface water bodies (3). This phenomenon lends itself to an additional explanation for the improved water quality associated with high density development. Because sewer systems are correlated with the percentage of high density development, seepage of nutrients into ground- and surface water is inhibited in highly developed areas.

Hydraulic retention time was significantly correlated with all three water quality parameters. Furthermore, the multiple regression analysis suggests that HRT is one of the predominant drivers of water quality for each of the three water quality parameters. Since a larger HRT corresponds to improved water quality, it would be worthwhile to examine HRT more closely. The average HRT of lakes in this study is approximately one year, but ranges from 13 days to 3 years. A large HRT would correspond to a large volume lake or a small body with a low flushing rate. The tendency of HRT to be a primary driver of water quality probably illustrates that the nature of the lake itself plays a large part in the impact of the watershed changes may have on water quality. One possible mechanism that links HRT to water quality is the stability of the thermal regime and stratification. Deeper lakes in the region develop very distinct thermoclines during the summer, inhibiting the mixture of nutrients throughout the water column, and possibly resulting in a low TP sample at one meter depth. Deeper lakes also possess nutrient sinks in the sediments, as the sediments are not easily mixed with the epilimnion of the lake. Stable thermoclines occur in deeper lakes, and lakes with greater volumes. The association of thermal stratification, nutrient sinks, and water quality may be reflected in the analysis of HRT. Further analysis of the thermal and mixing regimes and morphology of these lakes might reveal further relationships with water quality.

A possible deficiency in this study is the scale of land use assessment within the watershed, and the criteria that defined those land uses. Using a different assessment methodology might have lent itself to more revealing results. For example, Landsat TM imagery has been used in other studies of lake water quality (10), and investigation of alternative methods to assess land use might be helpful in future studies. Additionally, the present study focused only on a land use assessment of the watershed. A comprehensive watershed assessment would need to focus on all processes that form the watershed—habitat forming processes, sediment and hydrologic regime, nutrient regime, and solar input. Due to reasons of time and data availability, this full

watershed assessment was not attempted in this study, but could provide more comprehensive results.

Conclusions

The collective findings of this study are noteworthy and meaningful. The results of the multiple regression analyses explain 37% of the variability of Secchi depth, 34% of the variability of Chl-a, and 25% of the variability of TP. The results are significant, but not complete. It is obvious that there are additional processes that this study fails to model. More than half of the variability of water quality was not explained by this study, indicating that the processes that control lake health are complex and interwoven, and not well described by general relationships or simplified hypotheses.

Alternative hypotheses include examination of the state of wetlands associated with the lakes. Wetlands filter out chemicals and nutrients from surface waters (11). Degraded wetlands are known to be a source of nutrients to associated surface water bodies (12). It is possible that degraded wetlands fail to filter out nutrients or contribute to nutrient loading, resulting in degraded lake water quality. As was suggested earlier, examination of surface water management and CSOs in these watersheds may explain the health of the lakes more extensively. Further examination of the effects of septic and sewer systems on lakes, as was described by Moore, et al. in 2003 (9), may reveal more information on the processes that affect lake health and quality. Other hypotheses that have been suggested include road density (13), spatial variation of lake quality across lake chains (14), and the individual geomorphologies of lakes (15).

The findings of this study and resulting implications for land use planning and management would not have been possible without the extensive collection of water quality data by King County staff and volunteers, maintained by the King County Lake Stewardship Program. This collection of data provides a long-term record of water quality and allows such studies as this to aid in future planning and management.

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