Phosphorus Mass Balance for the Washington-Sammamish Watershed, Washington

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Introduction

The objective of PRISM (Puget Sound Regional Synthesis Model) is to create a "virtual Puget Sound" that captures the interaction between physical, chemical, and social data in the region. This project is an interdisciplinary effort by the University of Washington to model the complexity of the region on a spatial and temporal scale. The ultimate product is a "tool" which can be used to evaluate regional changes (such as land use, climate/precipitation, and population growth) on the operation of the entire system. King County is making a similar effort on a watershed scale with the Lake Sammamish-Washington Assessment and Modeling Program (SWAMP).

An important element of SWAMP is nutrient cycling, specifically the impacts of phosphorus loading to the watershed. Phosphorus is an important nutrient for plants and animals. An over abundance of phosphorus in surface waters can lead to excessive growth of aquatic plants that can lead to water quality problems, such as depleted dissolved oxygen or increased surface water temperatures (1). A phosphorus budget evaluates the inputs and outputs of the system, which is useful for estimating storage in the watershed, quantifying phosphorus inputs to the lakes, and evaluating problems and solutions. The objective of this study is to construct a phosphorus mass balance for the Washington-Sammamish watershed.

Study Area

The majority of the Washington-Sammamish watershed is located in King County, Washington, with a small portion in Snohomish County. The area of the watershed is approximately 608.5 mi^2 or 1576 km^2. The watershed is composed of two subwatersheds: Cedar River-Lake Washington and Lake Sammamish. Each watershed is briefly described to add perspective to the study undertaken.

The Cedar River-Lake Washington watershed is approximately 385.5 mi^2 or 998.4 km^2. A map of the watershed is included in Figure 1. The focus of the watershed is Lake Washington, which is the largest lake in western Washington. The primary tributaries of Lake Washington are the Cedar and Sammamish Rivers. The outlet of the lake to the Puget Sound is the Ballard Ship Canal.

The Lake Sammamish Watershed (see Figure 2) has an area of approximately 223 mi^2 577.6 km^2. Lake Sammamish is the major water body within the watershed. Issaquah Creek and the Sammamish River are the lake’s primary input and output, respectively.

The nature of SWAMP enables the sub-watersheds to be merged into one single watershed. All of the research and data presented is based on this assumption. Initially, land use practices are categorized over the watershed to determine what phosphorus inputs (fertilizer, animal waste, septic systems and atmospheric deposition) and outputs (crop harvesting and streams) to research. Land use in the watershed consists of 32% Urban, 25% Rural, 7% Parks, 34% Forest, and 2% Agriculture. Figure 3 outlines the land use proportions for the entire watershed (2, 3, 4). The watershed consists of 16% impervious surface area (2, 3). Please note that the majority of the watershed is comprised of urban and forested areas.

Approach

The first step is to determine the control volume boundary of the Washington-Sammamish watershed. The group set the boundary around the entire watershed. Within the boundary the control volume consists of the terrestrial surface area and includes the streams and watershed plants, but excludes Lake Washington and Lake Sammamish. The inputs and outputs are researched based on this boundary.

Next, a list of potential phosphorus inputs and outputs is compiled. A schematic diagram of the Washington-Sammamish watershed phosphorus inputs and outputs is presented in Figure 4. The list is divided among the group members and independently researched. The research methods and results are presented throughout the following sections of the paper.

Finally, the phosphorus data is compiled into a budget to determine the total phosphorus inputs and outputs to the watershed. The phosphorus storage in the watershed is calculated from these results. The research uncovers the limitations of current phosphorus budget studies. These limitations are summarized into a list of future research needs.

Inputs

Fertilizer Use

Phosphorus inputs to a watershed can be heavily influenced by the type and scale of fertilizer used in the watershed. Fertilizers are rich in nitrogen and phosphorus, which are important nutrients for plant and algal growth. The final use of a fertilizer dictates the relative ratios of nitrogen to phosphorus concentrations. To facilitate the mass-balance analysis, fertilizer use is sub-divided into two main categories, Agricultural and Urban. The following analysis is conducted using values for Total Phosphorus (TP), since this data was most readily available. In the Washington-Sammamish watershed, agriculture land use is a small percentage of the total area. Therefore, it is not necessary to further sub-categorize agricultural fertilizer application by the crops being grown.

Urban land use, which is the predominant land use in the watershed, is classified into sub-categories based upon the different urban land use types and the application method used. A significant number of landscape maintenance firms use a different mixture ratio in the fertilizer they apply. This fertilizer is specifically formulated for lawns to utilize less phosphorus because nitrogen is more critical for grass growth. If, however, a household decides to save money and buy the fertilizer from a retail store, the formulations are such that they can be applied to a wide variety of plants, resulting in higher levels of phosphorus in the fertilizer.

The problem with such a detailed classification system is obtaining reliable, accurate, and meaningful data on both spatial and temporal scales. This proved to be one of the most difficult challenges in the study. There are well documented statistics for crop fertilizer use due to the regulations on agricultural productions. In contrast, there is very little data available for household lawn care. Considering the degree of urbanization in the Washington-Sammamish watershed, this could prove to be a large component of the overall phosphorus input. For all situations, data is collected from as many different sources as possible.

Agriculture

Data for agricultural fertilizer application is evaluated from three different sources:

- EPA Index of Watershed Indicators (IWI) (4)
- USGS Water-Quality Assessment of the Puget Sound Basin, Washington, Nutrient Transport in Rivers, 1980-93. (1)
- USDA Census – 1997 (5)

The EPA analysis provided data on nitrogen application in the Washington-Sammamish watershed. Using a ratio factor of 9:1 for N:P, the phosphorus yield is 6.22 tons/yr. The USGS assessment found phosphorus input to be 12.3 tons/yr while the USDA Census study concluded that 13.2 tons/yr entered the Lake Washington watershed from agricultural fertilizers. Data from the USDA study required extrapolation because fertilizer sold in the county is given as a total dollar value ($587,000 in 1997). The retail cost of fertilizer obtained from Home Depot is $7.87 for an 18 lb bag. It is understood that this is more expensive than what farmers would normally pay and thus would cause final estimates to be lower than actual. A N:P ratio of 9:1 is used to determine the amount of phosphorus entering the county. This data is scaled to the watershed based on area.

Urban

The analysis of urban fertilizer use is based on information provided in the USGS study. Fertilizer applied by commercial lawn care companies use an N:P ratio of 100:1. This ratio results in a phosphorus yield of 0.06 lb/1000 ft^2 - yr. (This is 1000 ft^2 of actual applied area as opposed to area of watershed). This yield must be considered in comparison to people who do not procure the services of a lawn care company, but rather apply fertilizer themselves. It is extremely difficult to characterize how many households use fertilizer, how often and at what levels it is applied. These all combine to introduce large uncertainties in the analysis. Retail fertilizer has an N:P ratio of 9:1, which is far greater than for commercial fertilizer. This gives a P-loading value from retail fertilizer use of 0.67 lb/1000 ft^2 - yr.

It is difficult to determine the fraction of households using fertilizer for lawn care. Therefore, possible phosphorous input is constrained between 100% use of retail fertilizer as the maximum and 100% use of commercial fertilizer as the minimum. The USGS study (1) assumed that 1/8 of urban land area is fertilized within a typical watershed. This results in an overall loading to the Washington-Sammamish watershed of 13.79 to 154.05 tons/yr.

Wet and Dry Deposition

Data used to calculate the wet and dry atmospheric phosphorus contributions to the Washington-Sammamish watershed came from the 1985 USGS report (6), *Data collected by USGS during a study of urban runoff in Bellevue, WA, 1979-1982*. Although this is an older reference, it is the best source for atmospheric phosphorous deposition in the watershed. As part of the urban runoff study, three catchments in Bellevue, WA (located within the watershed) were monitored for wet and dry deposition from October 1979-January 1982. During the period of the study, data was collected on a monthly basis. The land use for two of the areas is single family residential, and the third is commercial. The annual total phosphorus load to the Washington-Sammamish watershed was estimated by averaging the annual total phosphorus (TP) deposition rates at each of the three sites. Average annual contributions are calculated to be 16.4 US tons of phosphorus per year from wet deposition and 30.4 US tons of phosphorus per year from dry deposition, resulting in a total contribution of 46.8 US tons of phosphorus per year.

The 1998 U.S. Geological Survey (USGS) report (1) also calculated values for phosphorus loading from atmospheric deposition, but came up with a higher total contribution. In the 1998 report, the 1979-82 Bellevue data is referenced for the phosphorus contribution from wet deposition. The dry deposition contribution is calculated using a wet-to-dry ratio and an urban correction factor. The source or development of the correction factor is not discussed in the report, but it is assumed to account for the high percent of urbanization that has occurred in the watershed since the Bellevue study. Incorporation of the urban correction factor results in a higher total phosphorus contribution of 92.85 US tons of phosphorus per year.

Animal Waste

The phosphorus contribution to the Washington-Sammamish watershed from animal waste is determined from data collected by the U.S. Department of Agriculture (USDA) for King County and the King County Livestock Coordinator (7). It is assumed that the contribution of phosphorus from the small portion of the watershed that lies within Snohomish County is negligible. The USDA/National Agricultural Statistics Service 1997 census (5) for King County provided the number of contributing farm animals, excluding horses. The King County Livestock Coordinator (7) provided information on which of the listed animals are actually in the Washington-Sammamish watershed. Only beef cows are found to be significant.

Table 1: Quantification of Phosphorous Input to the Watershed from Animal Waste

	County Values				Watershed Values	
Animals	Number of Animals	Number of Animals per AU	Tons Manure per AU	TP loading lb/ton manure	TP load Ton/yr	TP load ton/mi^2/yr
Beef cows	[5] 2370	[19] 1	[19] 11.5	[19] 3.79	14.56	0.0235
Horses	[7] 30000	[20] 1	[20] 9	[20] 2.79	106.22	0.1716
				TOTAL	120.78	0.1951

King County also provided information on the number of horses in the county, which was not provided by the USDA report, but are significant in the watershed. The number of beef cows, (converted to number of animal units (AU) based on an average weight of 1000 lb.) was used in conjunction with the manure phosphorus load for its animal category (8) to determine the phosphorus contribution from beef cow waste. The phosphorus loading from the manure of various farm animals was calculated by the USDA/National Resource Conservation Service. The phosphorus in horse waste is calculated from a report in the 1999 North Carolina Agricultural Chemicals Manual (9). The contribution of phosphorus from pet waste is explored, but insufficient information was found. It is also determined that with laws requiring owners to pick up after their pets, the total contribution to the watershed would be minimal. The calculated phosphorus loads in King County from each animal were normalized to the area of the Washington-Sammamish watershed to determine the phosphorus loading to the watershed. This value is found to be 121 US tons of phosphorus (TP) per year (see Table 1).

A 1998 USGS report (1) found the contribution of phosphorus to the watershed from manure to be 48.64 US tons per year based on county data for animal populations during 1982, ’87, and ’92. These values are averaged over the number of years of data, allocated to land-use areas in the river basin, and multiplied by the county phosphorus loading rates.

Septic Systems

Septic systems are an alternative to discharging household wastewater to a sewer. They are relatively simple systems, and are less costly than a city sewer connection. However, septic systems have the potential to input large amounts of pollution to the watershed. They are generally acceptable for rural areas, but as population density increases, the pollution from septic systems can become significant. Conventional septic systems have a septic tank, where household wastewater receives primary treatment. Systems constructed before 1975 in King County have one tank, and most systems built after 1975 have dual in-line tanks. Most septic tanks need to be pumped every 3-5 years. If they are not pumped regularly, solids can accumulate in the tank, and overflow into the drainfield. Drainfields are gravel-filled trenches with perforated pipe laid in them. They are typically buried in the homeowner’s back yard. Soil below the drainfields filters the effluent from the septic tanks. When conditions do not allow for the use of traditional drainfields, alternatives include sand filter systems and mound systems, although traditional drainfields are the most common.

There is a difference of about 116,000 between the population in King County and the number of people served by sewer connections. (21) Typically, septic systems are designed for 60 gallons per day per capita (14). According to a study by Seabloom and Engeset (15), the average total phosphorus (TP) concentration in the effluent of septic systems in the King County area is 24.7 mg/L. Multiplying these values out, and using appropriate unit conversions, the total phosphorus input into King County by septic systems is approximately 265 tons annually. However, the Washington-Sammamish watershed does not encompass all of King County. Assuming half of the septic systems in King County are in the Washington-Sammamish watershed, the total mass of phosphorus entering the watershed from septic systems is 132.5 US tons per year. Assuming that half the systems in King County are in the watershed may be an overestimate. Normalizing the estimated total phosphorus input from septic systems to the Washington-Sammamish watershed area gives a total phosphorus input of approximately 73.6 US tons annually. These estimates assume that all septic systems are maintained regularly, and are not leaking. Septic systems are one of the largest phosphorus inputs to the watershed.

Outputs

Crop Harvest

It is presumed that agricultural crops harvested within the Washington-Sammamish watershed are exported outside of the watershed and are considered a P output. The crops harvested in the watershed are assumed to be proportional to the crops harvested in King (8) and Snohomish Counties (9). The type and quantity of each crop harvested within each county is taken from the 1997 Census of Agriculture (5) and the 1997 USDA Vegetable-Annual Summary (10). The data for phosphorus contained in each crop is provided by the USDA Agricultural Handbook (11) and the Resource Assessment and Strategic Planning Working Paper (12). These numbers are used together with the quantity of crops in each portion of the watershed to determine the total phosphorus harvested within the watershed.

The phosphorus exported from the harvest of each agricultural crop in the Washington-Sammamish watershed is organized and tabulated by county in Table 2. Estimates of the total phosphorus exported from the watershed range from a maximum of 32.73 tons per year (63,781 pounds) to a minimum of 0.83 tons per year (1657 pounds). Of the minimum estimate, approximately 0.51 tons per year is exported from the King County portion of watershed and 0.32 tons per year from the Snohomish County. From the maximum estimate, approximately 24.98 tons per year are exported from King County and 7.74 tons per year are exported from Snohomish County.

If it is assumed that all the agricultural crops harvested within the watershed are exported outside of the watershed and are not used as feed within the watershed, the phosphorus output is 32.73 tons per year. However, if the various types of hay and silage are used as feed within the watershed, then vegetables are the only agricultural output. In this case, the phosphorus export is estimated at 0.83 tons/yr. Figure 5 illustrates the quantity of phosphorus harvested in all silage and hays in contrast to the quantity of phosphorus harvested in vegetables. Approximately 2.54% of the phosphorus are harvested in vegetables and the remaining 97.46% are harvested in silage and hay.

Caveats:

1. The quantity of crops harvested in the watershed is scaled down according to the quantity of crops and the amount of cropland in each county in the watershed. This procedure may under or overestimate the amount of agricultural land of the watershed, which would lead to an inaccurate estimate of the phosphorus harvested within the watershed. Approximately 1.5% of King County (8) and 5% of Snohomish County (9) is agricultural land. King County land use maps (13) indicate there is approximately 1-2% agricultural land in the watershed. However, it is quite likely that the estimates of phosphorus are within range, due to the small differences in agricultural land in the two counties and the watershed.
2. It is unknown whether the silage and hay are used for feed inside or outside of the watershed. There is approximately 31.9 tons of phosphorus that have potential to impact the mass balance in the watershed. If the hay/silage is kept within the watershed, it is not considered and import or an export. However, if the hay/silage is sold outside of the watershed, it is considered an export. This leaves a large range of phosphorus outputs from the watershed.

Combined Sewer Overflows

In certain areas of Seattle the storm and sanitary sewers are collected in one pipe, a result of old sanitary engineering practices. When heavy rains fall, combined sewer pipes fill up, and some of the combined sewage is bypassed straight to the nearest lake or stream. Two combined sewer overflows (CSO) discharge to Lake Washington: sites named Henderson and Belvoir. King County is planning to eliminate the Henderson CSO by 2003. Since raw sewage is relatively high in phosphorus, CSO’s were considered in the phosphorus budget.

Flow from these two CSOs is obtained from King County for water years 1996-7 and 1997-8 (16); King County measures these flows. Annual overflow volumes are shown in Table 3.

Table 3. Annual CSO Volumes

Water Year	Henderson (million gallons)	Belvoir (million gallons)
1996-7	13.6	0.2
1997-8	2.2	0.2

For water year 1997-8, 2.4 million gallons of raw sewage is discharged to Lake Washington. According to King County, the average total phosphorus (TP) concentration of raw sewage during peak storm events (when CSO discharges occur) is approximately 5 mg/L. With appropriate unit conversions, this corresponds to a phosphorus mass loading of 0.29 tons per year for 1996-7, and a total phosphorus loading of 0.05 tons per year for 1997-8. Therefore, CSO discharges are a nearly negligible part of the overall P budget. CSO volumes are also expected to decrease as a result of continuing combined sewer separation projects.

Stream Export into Lakes Washington and Sammamish

Fifteen major streams discharge into Lake Washington and several streams discharge into Lake Sammamish. Data is sketchy for many of the streams, with the exception of Issaquah Creek, which has daily phosphorus concentrations for a period of one year. The Issaquah Creek data is obtained from the thesis of Stephen Butkus (17). Since Issaquah Creek contributes approximately seventy percent of the flow to Lake Sammamish, it is assumed that the same is true for phosphorus loading. This gives a stream phosphorus export to Lake Sammamish of 13.6 tons per year. However, this may be an overestimate for current conditions since the data are for 1986-7.

Lake Washington streamflows are developed from an index by a peer group analyzing phosphorus export from streams (18). The index is used to generate daily streamflows for the significant streams discharging to Lake Washington. Since the total phosphorus data for most streams are only bi-monthly, geometric mean phosphorus concentrations are used for all of the streams discharging to Lake Washington. The streamflows are multiplied by the geometric mean phosphorus concentration for each day, and then summed for each year for the period from 1991-1995. The average of the five annual loadings is taken as the TP loading for that stream. The calculated average annual phosphorus export to Lake Washington from streams is 32.3 tons per year. This gives a total stream export to the two lakes of 45.9 tons per year.

Results

The results of the analysis are presented here in **Table 4**:

Washington-Sammamish Watershed			
HUC 17110012			
Area 608.5 sq. miles			
	Elements	**Minimum (ton P/yr)**	**Maximum (ton P/yr)**
Inputs	Fertilizer	20.01	167.25
	Agriculture	6.22	13.2
	Urban	13.79	154.05
	Wet/Dry Deposition	46.8	92.85
	Animal Waste	48.64	120.7
	Septic Systems	56.3	132.5
	Total Inputs	**171.75**	**513.3**
Outputs	Crop Harvest	0.83	32.73
	Combined Sewer Overflows	0.05	0.29
	Stream Export	45.9	45.9
	Total Outputs	**46.78**	**78.92**
Storage	**Total Storage**	**124.97**	**434.38**
	Percent Storage	**72.76**	**84.62**

Conclusion

The results, displayed in Table 4, indicate that more phosphorus is input to the watershed than exported from the watershed. In fact, approximately 73-85 % of the phosphorus that is input to the Washington-Sammamish watershed is retained. The principle inputs to the watershed are currently from septic systems, urban fertilizer, animal waste and atmospheric deposition. The uncertainty of data available for septic systems in the watershed and urban fertilizer use necessitates further investigation to obtain more reliable values of phosphorus input.

Future Research

Future research needs to include:

- Fertilizer – more complete data and sample collections in King and Snohomish Counties. The data in this section varies greatly.
- Wet/Dry Deposition – The values presented in this section are also highly variable. The USGS values are probably most accurate because these numbers are based on a spatial mathematical analysis. The lower values were derived almost a decade ago, before Bellevue was highly urbanized.
- Septic Systems – the data available here are vague. This is one of the highest sources of phosphorus in our budget.
- Crop Harvest – Due to time constraints, investigation into the final destination of animal waste and hay/silage is not performed. As a result it is possible that

phosphorus may be double or triple counted in the overall mass balance. To provide direction for future research, five separate phosphorus scenarios are outlined below. The total agricultural phosphorus inputs to the watershed for each scenario are calculated in Table 5. Agricultural phosphorus input can vary from a maximum of 101.25 tons per year, Scenario B, to a net output of 0.83 tons per year, Scenario E, via export of vegetables.

Scenario A – The minimum commercial fertilizer is used by the local farmers; the hay/silage is grown and exported; the waste from the horses/cows is considered an input.

Scenario B – The maximum commercial fertilizer is used by the local farmers; the hay/silage is grown and exported; the waste from the horses/cows is considered an input.

Scenario C – No commercial fertilizer is used by the local farmers; the hay/silage is grown and exported; the waste from the horses/cows is used for manure fertilizer and considered and input.

Scenario D – No commercial fertilizer is used by the local farmers; the hay/silage is used for feed for the animals in the watershed (only the vegetables are an output); the waste from the horses/cow is not an input or an output because they consume the P that was originally grown in the watershed; the manure is used for fertilizer.

Table 5 : Agricultural P Input/Output Scenarios

Input/Output	A	B	C	D	E
Commercial Fertilizer	6.22	13.2	0	0	13.2
Hay/Silage	**32.73**	**32.73**	**32.73**	**0.83**	**0.83**
Animal Waste	120.78	120.78	120.78	0	0
P Inputs	94.27	101.25	88.05	-0.83	12.37

** The bold numbers are outputs

Scenario E – The maximum commercial fertilizer is used by the local farmers; they hay/silage is used for feed for the animals in the watershed (only the vegetables are an output); the waste from the horses/cows is not an input or output because they consume the P that was originally grown in the watershed.

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