A Department of Ecology Report

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Estimates of Nitrate Loading to South Puget Sound by Groundwater Discharge

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Abstract

The annual mass of dissolved nitrate-nitrogen (nitrate) transported to the southern portion of Puget Sound by direct groundwater discharge was estimated to support the South Puget Sound Nutrient Model Study modeling effort. Data from the region south of the Tacoma Narrows was evaluated to delineate the area from which groundwater flows directly to Puget Sound. This "area of contribution" was subdivided into 19 individual recharge/discharge zones. An estimated range of annual groundwater discharge volume was developed for each of the zones using a water budget approach. An annual groundwater discharge volume was additionally developed for underflow from the Nisqually River alluvial aquifer. Groundwater quality data was compiled, and a representative nitrate concentration was assigned for each zone. Estimates of discharge volume and nitrate concentration were then integrated to determine annual loading to the South Sound.

The loading calculations predict an annual mass of nitrate discharging to South Puget Sound via groundwater transport between approximately 160,000-190,000 $kg_{nitrate}$/yr. These values are based on available data, and were calculated using a number of simplifying assumptions regarding the behavior of nitrate in the subsurface, and the movement of groundwater in a complex hydrogeologic setting. The use of public water-supply well data to estimate groundwater quality in the study area remains the greatest source of uncertainty in the estimates. Due to concerns that the Washington State Department of Health (WDOH) data under-predicts the nitrate concentration in groundwater, the load estimates may best define the lower bound of current conditions. Predictions of annual load were also developed to highlight the consequences of rising nitrate concentrations with time.

Introduction

This report describes the results of an analysis of nutrient loading by direct groundwater discharge to the southern portion of Puget Sound. This work was conducted in support of the South Puget Sound Nutrient Model Study project. The goal of the South Puget Sound Nutrient Model Study project is to characterize the hydrodynamics and water quality of, and pollutant loading to, southern Puget Sound (Cusimano, 1998). Within the larger study area of the South Puget Sound Nutrient Model Study project (Figure 1), groundwater loading estimates were developed for that portion of Puget Sound that lies south of the Tacoma Narrows (South Sound).

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by Charles F. Pitz *Waterbody No. WA-13-1010* *Ecology Report #99-348*
December 1999 *(additional numbers on page 17)*

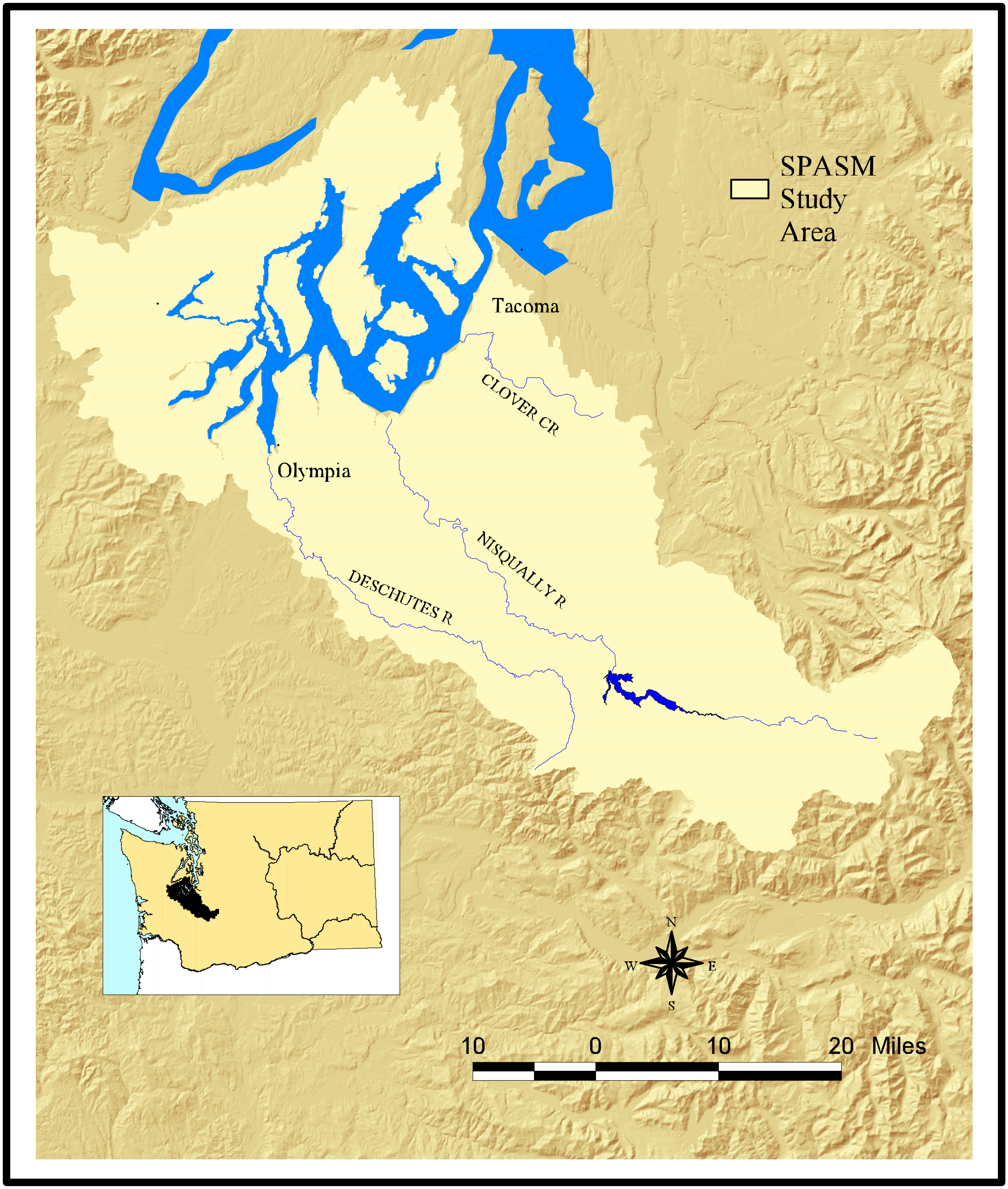

Figure 1 - Study Area Map
South Puget Sound

The Watershed Studies Unit of the Washington State Department of Ecology (Ecology) Environmental Assessment Program requested that an estimate be developed for the mass of nutrient that is annually loaded to South Sound via groundwater discharge. Nutrient loading to Puget Sound by groundwater transport occurs via two major flowpaths: as direct discharge to shoreline areas, and as baseflow to tributaries that eventually drain to Puget Sound.

This study focuses only on the direct discharge pathway. Nutrient loading via baseflow to tributaries will be accounted for during the South Puget Sound Nutrient Model Study project through measurement or estimation of surface water discharges to South Sound. Data may be available to evaluate baseflow contributions of nutrients to tributaries within the South Sound watershed, but such an effort is beyond the scope of this report.

Assumptions

The estimates presented in this report are founded on a number of important simplifying assumptions.

1. It is assumed that groundwater discharges to Puget Sound via two major flowpaths: as direct discharge (e.g., via underflow in tributary basins, seepage from shoreline bluffs, submarine input), and as baseflow to tributaries that eventually drain to Puget Sound.

   Only direct discharge contributions were estimated for this study.

2. It is assumed that the key measure of concern for this study is the mass of dissolved nitrate-nitrogen (nitrate) discharging annually to South Sound. Due to its fate and transport characteristics, nitrate is typically the dominant nutrient detected in groundwater, both in concentration and three-dimensional distribution (Freeze and Cherry, 1979; Hem, 1989). Groundwater quality data from wells within the study area indicate that other nutrients such as ammonium and phosphorus are not present at significant concentrations except in localized areas (Drost et al., 1998; Vasey, 1996; USGS, 1998). The fate and transport characteristics for these constituents suggest that they are largely attenuated or transformed in the subsurface prior to discharge to Puget Sound (Freeze and Cherry, 1979; Drost et al., 1998; Hem, 1989; Vasey, 1996).

3. It is assumed that dissolved nitrate in groundwater will behave conservatively during transport, i.e., there is no significant attenuation of the concentration of nitrate along the groundwater flowpath. Further, this study does not address attenuation of nitrate load that may occur at the discharge interface.

4. It is assumed that nutrient loading to Puget Sound via groundwater discharge, from a *mass* standpoint, occurs predominantly within the uppermost portions of the regional aquifer system (<500 feet below ground surface). Considering the length of the flow-path, age and recharge source of water, as well as intervening attenuation effects, discharge by deeper regional groundwater flow is not judged to contribute a significant nutrient load to Puget Sound. Groundwater quality data from deep wells located within the study area confirm that nitrate is largely below detectable concentrations in the deeper regional aquifers discharging

to Puget Sound (Drost et al., 1998; Tesoriero and Voss, 1997; USGS, 1998; Brown and Caldwell, 1985; WDOH, 1998). Groundwater underflow from regions upgradient of the area of contribution, and eventual submarine discharge from the deepest portions of the aquifer system, is therefore ignored.[1] No groundwater quality data were used from wells completed more than 500 feet below ground surface.

5. It is assumed that annual recharge is in dynamic equilibrium with annual discharge (prior to adjustment for consumptive diversions); that is, inflow to the groundwater system is equal to outflow and there is little or no change in total storage.

Methodology

Estimation of the nitrate mass loaded to the South Sound by groundwater transport is based on the integration of estimated discharge volume and nitrate concentration. Outlined below are the procedures that were used to estimate these variables.

Estimation of Groundwater Discharge Volume

A water budget approach was used to develop an estimated range of annual groundwater discharge to the South Sound. To first delineate areas where groundwater flows directly towards South Sound (versus those areas where groundwater is judged to be discharging to tributaries), an "area of contribution" was mapped. Groundwater elevation data, available flow direction maps, subsurface geologic information, and ground surface topography from throughout the study area were evaluated for this purpose (Tesoriero and Voss, 1997; Drost et al., 1998; Drost., 1999; Vaccaro et al., 1998; Walsh et al., 1987; Lum, 1984; Pearson and Dion, 1979; Brown and Caldwell, 1985; Garling et al., 1965; Molenaar and Noble, 1970; Carson et al., 1975; Lum and Walters, 1976). The "area of contribution" determined for direct groundwater discharge to South Sound is shown in Figure 2. All groundwater inland of the area of contribution was assumed to be intercepted by surface water features, or discharging as deep, uncontaminated underflow.

The area of contribution was subdivided into 19 distinct zones around the perimeter of South Sound. The total estimated minimum and maximum annual volume of recharge to each zone was determined using Geographic Information System (GIS) analysis of annual recharge values developed by the U.S. Geological Survey (USGS) (Vaccaro et al., 1998). The individual recharge/discharge zones used for this study are shown in Figure 2.

For the purposes of this study, it is assumed that 95% of the water recharging the area of contribution shown in Figure 2 discharges directly to Puget Sound. This value was chosen on the basis of data that indicate that approximately 5% of the total volume of recharge in the

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[1] Discharge volume estimates presented later in the report do not represent the total volume of groundwater discharged to Puget Sound, only that portion assumed to be carrying measurable levels of dissolved nitrate.

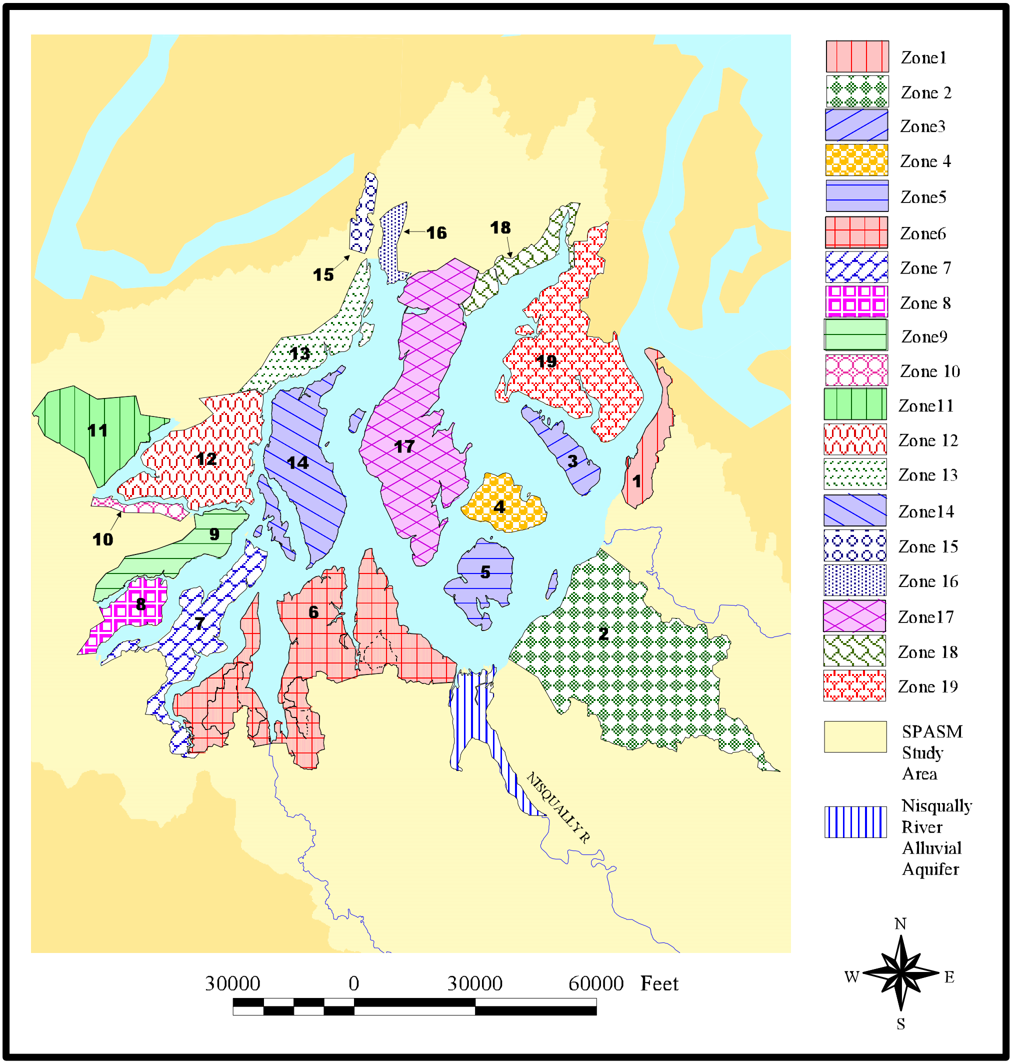

Figure 2 - Groundwater Area of Contribution
Recharge/Discharge Zone Map
South Puget Sound

Puget Sound lowland is withdrawn by wells prior to discharge (Vaccaro et al., 1998). The remainder of the recharge is assumed to discharge to Puget Sound directly, without significant interception by streams and rivers. This approach does not explicitly account for secondary recharge via leakage from septic systems, sewer and water pipes, and other sources.

In addition to discharge from the 19 recharge zones shown in Figure 2, a Darcy flux estimate of the annual groundwater discharge by underflow was calculated for the Nisqually River alluvial aquifer (Figure 2; Table 1). Hydrogeologic data reviewed throughout the study area suggests that the Nisqually River valley is the only location where underflow occurs to the South Sound at a scale significant to the study. Data for the remaining major tributaries in the study area (e.g., Deschutes River, Clover Creek) suggest that groundwater adjacent to the lowermost reaches of these drainages largely discharges as baseflow before entering Puget Sound (Drost et al., 1998, Drost et al., 1999, Brown and Caldwell, 1985). The absence of significant underflow to South Puget Sound from other tributaries is in part due to the fact that they lack a well-developed alluvial aquifer like that present in the lowermost portion of the Nisqually valley.

Table 1. Estimation of Annual Discharge to Puget Sound by Underflow Nisqually River Alluvial Aquifer.

K [1] **(ft/day)**	**b** [2] **(ft)**	**T (ft^2/day)**	**W** [3] **(feet)**	**dh/dl** [1]	**Q (ft^3/day)**	**Q (L/year)**
17	100	1700	10000	0.0011	18700	1.93E+08

Q = T*W(dh/dl)
Q = approximate quantity of water moving to Puget Sound as underflow (ft^3/day)
T = aquifer transmissivity (K*b) (ft^2/day)
K = average hydraulic conductivity (ft/day)
b = approximate saturated aquifer thickness (feet)
W = approximate aquifer width (feet)
dh/dl = hydraulic gradient (dimensionless)

References

[1] Drost, B.W. et al., 1999, U.S. Geol. Surv. Water Resources Investigations Report 99-4165
[2] Drost, B.W. et al., 1998, U.S. Geol. Surv. Water Resources Investigations Report 92-4109 (Revised)
[3] Walsh, T.J. et.al., 1987, Geologic Map of Washington-Southwest Quadrant (electronic GIS coverage)

The resulting estimated annual minimum and maximum recharge and discharge volumes for each of the 20 discharge zones is presented in Table 2, Columns B, C, D, and E

Estimation of Groundwater Nitrate Concentration

Groundwater quality information from the area of contribution was initially collected and evaluated from the Washington State Department of Health (WDOH) Public Water Supply Database (WDOH, 1998), and the USGS National Water Information System Database (USGS, 1998). These data sets were first screened to identify only those samples that were reported from wells less than 500 feet deep. The data sets were then further screened to identify only those

Table 2. Dissolved Nitrate Loading to South Puget Sound by Direct Groundwater Discharge – Estimates by Zone.

	A	B	C	D	E	F	G		H	I
Zone #	Area of Zone (km^2)	Estimated Minimum Volume of Annual Recharge (liters/yr)	Estimated Maximum Volume of Annual Recharge (liters/yr)	Estimated Minimum Volume of Annual Groundwater Discharge to Puget Sound (liters/yr)^A	Estimated Maximum Volume of Annual Groundwater Discharge to Puget Sound (liters/yr)^A	Number of Wells Used To Calculate Geometric Mean	Geometric Mean Nitrate Concentration of Zone WDOH Data (mg/L)^C		Approximate Minimum Annual Nitrate Mass Flux (kg/yr)	Approximate Maximum Annual Nitrate Mass Flux (kg/yr)
1	16	4.26E+09	5.97E+09	4.05E+09	5.67E+09	NA	0.52	*	2000	3000
2	128	4.91E+10	6.12E+10	4.66E+10	5.81E+10	29	0.52		24000	30000
3	13	6.18E+09	8.06E+09	5.87E+09	7.66E+09	11	0.65		4000	5000
4	17	6.56E+09	8.29E+09	6.23E+09	7.88E+09	NA	0.42	*	3000	3000
5	22	7.98E+09	1.02E+10	7.58E+09	9.67E+09	13	0.35		3000	3000
6	118	5.61E+10	7.27E+10	5.33E+10	6.91E+10	61	0.65		35000	45000
7	39	1.81E+10	2.32E+10	1.72E+10	2.20E+10	15	0.31		5000	7000
8	16	8.54E+09	1.06E+10	8.11E+09	1.00E+10	NA	0.42	*	3000	4000
9	25	1.18E+10	1.47E+10	1.12E+10	1.40E+10	NA	0.42	*	5000	6000
10	5	2.35E+09	2.89E+09	2.23E+09	2.75E+09	NA	0.42	*	1000	1000
11	40	3.84E+10	4.82E+10	3.65E+10	4.58E+10	29	0.52		19000	24000
12	57	2.95E+10	3.64E+10	2.80E+10	3.45E+10	19	0.25		7000	9000
13	28	1.18E+10	1.47E+10	1.12E+10	1.40E+10	17	0.32		4000	4000
14	56	2.47E+10	3.11E+10	2.35E+10	2.95E+10	NA	0.42	*	10000	12000
15	7	4.26E+09	5.35E+09	4.05E+09	5.08E+09	NA	0.42	*	2000	2000
16	8	4.51E+09	5.46E+09	4.28E+09	5.19E+09	NA	0.42	*	2000	2000
17	103	4.72E+10	6.00E+10	4.48E+10	5.70E+10	110	0.30		13000	17000
18	17	7.57E+09	9.84E+09	7.19E+09	9.35E+09	41	0.31		2000	3000
19	77	3.01E+10	3.85E+10	2.85E+10	3.66E+10	206	0.39		11000	14000
Nisqually Underflow	NA	NA	NA	1.93E+08^B	1.93E+08^B	NA	1.50	*	300	300
Total	794	3.69E+11	4.67E+11	3.51E+11	4.44E+11	551			155300	194300

[A] – Assumes a 5% loss of recharge to withdrawals (Nisqually excluded).

[B] – See Table 1.

[C] – All non-detect samples were assumed to equal the reported detection limit (0.2 mg/L).

* – Assumed concentration, insufficient water quality data available for zone

samples collected on or after January 1, 1990.[2] Using these criteria, 551 unique results for nitrate plus nitrite as nitrogen (referred to in this report as nitrate due to the expectation that nitrite concentrations are very low relative to nitrate) were identified from the WDOH database for the area of contribution. A limited number of results were returned from the USGS database using these criteria. Due to the limited size of the data set, and the possibility that the sampling locations were biased to areas of known nitrate contamination, the USGS data were not used for this study.

Using the WDOH data, the geometric mean of the reported nitrate concentrations was calculated for each discharge zone having sufficient data (>10 results). This value was used as a representative measure of the bulk nitrate concentration of the groundwater discharging to Puget Sound. The nitrate concentration of all censored (non-detect) values was assumed to equal the reported detection limit (typically 0.2 mg/L). For zones that lacked sufficient groundwater quality data, the mean of the geometric means of all remaining zones (0.42 mg/L) was used for the loading calculations. In light of land use, and degree of development, an exception was made for Zone 1, where an alternative value of 0.52 mg/L (equal to the value calculated for the closest adjacent zone) was assumed. The nitrate concentration estimated for each of the discharge zones is presented in Column G, Table 2.

Insufficient groundwater quality data were available to calculate a representative nitrate concentration for the Nisqually River alluvial aquifer. Due to the agricultural land use of the lower valley, a comparatively high value of 1.5 mg/L was assumed to represent the bulk nitrate concentration of the groundwater discharging to Puget Sound from the aquifer (Table 2).

Results

Determination of Annual Groundwater Nitrate Flux Rate

The annual mass of dissolved nitrate discharging to South Sound from each zone was calculated by multiplying the estimated annual discharge volume (Table 2, Columns D and E) by the estimated nitrate concentration for the zone (Column G). The approximate range of annual dissolved nitrate load for each of the discharge zones, as well as for the study area as a whole, is presented in Columns H and I of Table 2. Table 3 contains estimates of the approximate range of annual nitrate mass flux per unit length of shoreline and per unit area for each zone. Figures 3 and 4 graphically exhibit the results presented in Table 3.

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[2] If multiple data values were available for an individual well, the most recent value was selected for use in the statistical analysis.

Table 3. Approximate Unit Annual Nitrate Mass Flux.

Zone	Approx. Length of Shoreline Bordering Puget Sound (km)	Approximate Annual Nitrate Flux Per Unit Length of Shoreline Using Min. Discharge) (kg/km/yr	Approximate Annual Nitrate Flux Per Unit Length of Shoreline Using Max. Discharge (kg/km/yr)	Approx. Area of Zone (km2)	Approximate Annual Nitrate Flux Per Unit Area of Zone Using Min. Discharge (kg/km2/yr)	Approximate Annual Nitrate Flux Per Unit Area of Zone Using Max. Discharge (kg/km2/yr)
1	14	140	210	16	130	190
2	12	2000	2500	128	190	230
3	25	160	200	13	310	380
4	20	150	150	17	180	180
5	36	80	80	22	140	140
6	111	320	410	118	300	380
7	51	100	140	39	130	180
8	18	170	220	16	190	250
9	22	230	270	25	200	240
10	9	110	110	5	200	200
11	9	2100	2700	40	480	600
12	36	190	250	57	120	160
13	29	140	140	28	140	140
14	76	130	160	56	180	210
15	4	500	500	7	290	290
16	8	250	250	8	250	250
17	75	170	230	103	130	170
18	20	100	150	17	120	180
19	56	200	250	77	140	180
	Total 631	Geomean 220	Geomean 260	Total 792	Mean 200	Mean 240

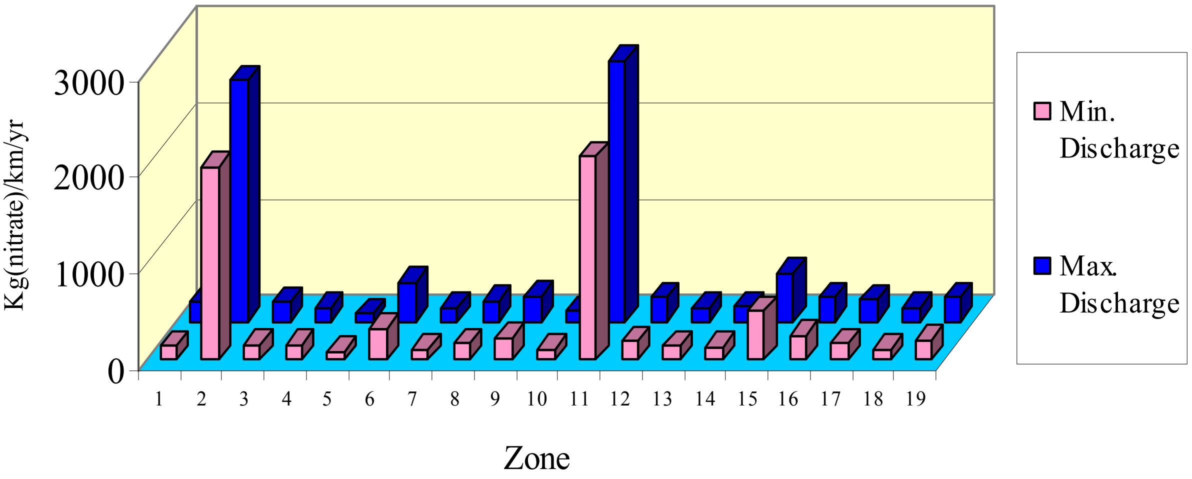

Figure 3 – Annual Nitrate Mass Flux by Groundwater Discharge Per Unit Length of Shoreline – South Puget Sound

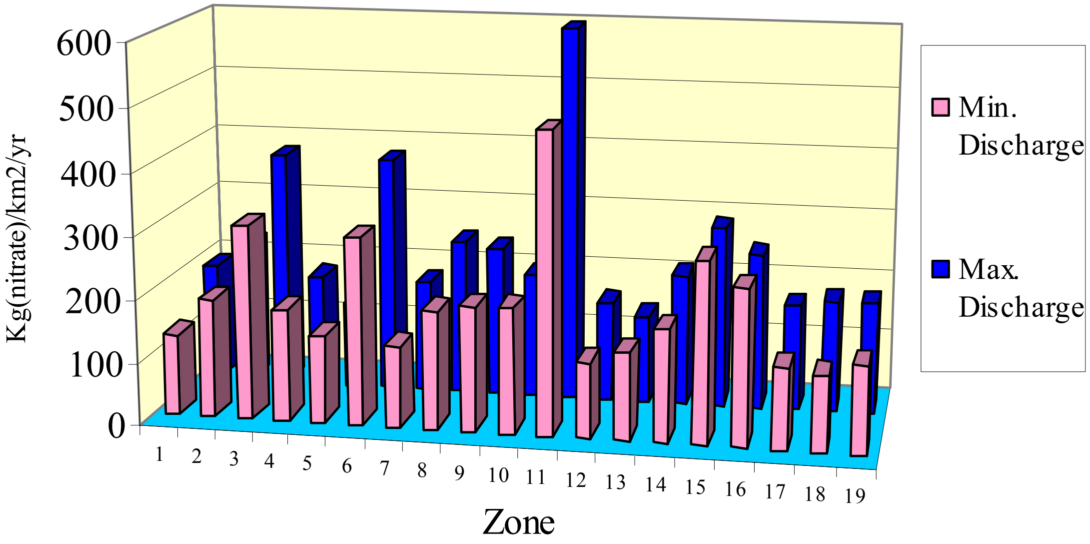

Figure 4 – Annual Nitrate Mass Flux by Groundwater Discharge Per Unit Area of Zone – South Puget Sound

Discussion

Accuracy of Groundwater Discharge Volume Estimates

Because groundwater discharge to Puget Sound is not readily measurable, the discharge volumes estimated in this report were derived using a water budget approach. As a result of the lack of data for the study area as a whole, the budget is simplistic; processes such as secondary recharge, evapotranspiration, or leakage to or from deeper aquifers are not explicitly included in the budget calculations.

To evaluate the accuracy of the discharge volume estimates presented in Table 2, the values were compared to other available large-scale predictions of discharge to Puget Sound. Drost et al., (1999) presented a numerical simulation of the groundwater flow system of the Thurston County area. The model domain encompasses the area defined by Zones 6 and 7 from this study (Figure 2). The model predicts a combined annual estimate of 1.08E+11 liters of submarine discharge (i.e. discharge occurring to offshore model cells) for the domain. Unlike the estimates presented in Table 2 of this report, this value does not account for groundwater that discharges from shoreline bluffs or seepage faces lying above sea level. The model value does, however, include groundwater discharge from the deepest portions of the aquifer system – a component of flow that is ignored in this study. As a result, the combined Zone 6 and 7 discharge range presented in Table 2 (7.05E+10 to 9.11E+10 L/yr) is not directly comparable to the estimate of submarine discharge predicted by the Thurston County model. Although above-sea level seepage to Puget Sound was not explicitly estimated, Drost (1999) has indicated that the maximum possible modeled volume for this component of discharge is 8.24E+10 L/yr. This would result in a total maximum possible model-estimated discharge of 1.91E+11 L/yr for Zones 6 and 7, just over a factor of 2 greater than the maximum estimated in Table 2.

Vaccaro et al., 1998, developed average unit estimates for submarine groundwater discharge to Puget Sound for a regional study of the Puget Sound Lowland aquifer system. These values were presented as a function of both shoreline length and area, and were derived in part from numerical models of type sections throughout the Puget Sound area. Applying these values to the Zone 6 and 7 areas shown in Figure 2, a total discharge volume from 3.57E+9 to 3.93E+10 L/yr is estimated. Applying these unit values to the area of contribution as a whole results in an estimate of submarine groundwater discharge ranging between 1.4E+10 to 1.86E+11. As with the Thurston County model values, these values are not directly comparable to the estimates in Table 2 (total = 3.51E+11 to 4.44E+11 L/yr). This is due to the fact that the model values include a deep component of flow ignored in this study, and do not include above-sea level shoreline seepage. While it is difficult to directly verify the discharge estimates presented in Table 2, the discharge values previously published do suggest that the predictions are on a reasonable scale.

The assumption that all water recharging the aquifer system discharges directly to Puget Sound (except water withdrawn for consumptive purposes) ignores discharge of groundwater to any surface water body within the area of contribution other than Puget Sound. Surface water flowing to Puget Sound from the many small groundwater supported streams present in the area of contribution is accounted for in this study as groundwater discharge. This approach was adopted to avoid double-counting surface water inputs to South Sound. The error introduced to the discharge volume calculation is unknown, but is considered to be small. The primary concern about this approach centers on the failure to account for the attenuation of nitrate (e.g., by plant uptake) that may occur once the groundwater has discharged into the stream environment. Therefore this error is judged to bias the loading estimates high.

Published water use data indicate that the assumption that only 5% of the recharge is withdrawn by wells is likely a low value for the more developed portions of the study area (e.g., Drost et al., 1998).

Accuracy of Groundwater Quality Estimates

The accuracy of the nitrate concentration estimates is judged to be the most significant factor influencing the accuracy of the load calculation. The dominant range of nitrate concentrations reported in wells from the study area is comparatively small (0-4 mg/L). However, due to the scale of the discharge volumes predicted, the load calculations are very sensitive to the concentration(s) chosen to represent the quality of the discharge water. The key to characterizing the accuracy of the concentration estimates lies in evaluating how well the available data are judged to represent true bulk subsurface conditions. Stratification or localized hot spots of nitrate are complicating factors in developing a representative concentration value for an individual zone.

The availability of groundwater quality data from the study area is one significant limiting factor in providing representative values for nitrate concentration. The number of nitrate data values per square kilometer used to estimate the bulk groundwater quality of a zone ranged between 0.3 (Zone 2) and 2.7 (Zone 19). The data density within the entire area of contribution averages slightly less than one data value per square kilometer.

Evidence suggests that groundwater nitrate concentrations have increased with time in certain areas of the Puget Sound Basin (Brown and Caldwell, 1985). Accordingly, only data collected after 1989 were used, to best reflect current conditions. To address the fact that nitrate concentrations reported for the study area are lognormally distributed, and that many of the data are censored (208 out of 551), the geometric mean was chosen as the best statistical method to represent the bulk water quality of a discharge zone. The use of a value equal to the detection limit for all censored values in the WDOH data is likely to bias the geometric mean higher.

The use of an assumed concentration value for a number of the discharge zones (Zones 1, 4, 8, 9, 10, 14, 15, 16, Nisqually) is a potential source of error. However, most of the zones that lacked sufficient data for calculating a statistically representative value are located in areas where population densities are low, and land use comparatively light (e.g., Fox, Harstene, Squaxin, and McNeil Islands; northeast Mason County). This suggests that nutrient inputs from the surface to the aquifer system (e.g., from leaking sewer pipes) are smaller in these zones than in the more developed areas. This in turn suggests that nitrate concentrations in the groundwater from these areas is more likely to reflect background conditions on a zone-wide basis. To acknowledge the more developed character of Zone 1, the geometric mean of the closest zone (Zone 2, 0.52 mg/L) was assumed for the loading calculations.

The data used for estimating the bulk groundwater quality of a discharge zone are drawn exclusively from public water-supply wells. The use of this data to represent the subsurface groundwater quality is judged to be the source of the greatest uncertainty in the loading estimates provided in this report. The wells reported in the WDOH database are typically designed to optimize water supply. Water-supply wells, in contrast to monitoring wells, are normally not designed to provide an accurate representation of the water quality of an aquifer system.

A significant concern regarding the WDOH data is the possibility that the nitrate concentration in the aquifer system is underestimated, particularly in the shallowest portions of a system. The larger pumping volumes and longer screen lengths for these wells may "dilute" the reported concentration of the constituent, by drawing water from larger portions of an aquifer or from adjacent surface water features (although this may in turn better represent the bulk water quality condition of the aquifer). Further, shallow public supply wells that exhibit elevated concentrations of nitrate are routinely deepened, or abandoned from use. As a result, the overall WDOH data set may be biased towards deeper, and/or less contaminated portions of the aquifer system. One hundred fifty-three of the 551 wells (28%) used for this study are completed less than 100 feet below ground surface, suggesting that the study data set is relatively evenly distributed throughout the vertical column of interest.

Erickson (1999) has noted evidence suggesting that water-supply wells may underestimate nitrate concentrations in shallow groundwater by as much as a factor of 3-4X. However, his data are drawn from monitoring wells that are in the near vicinity to nitrate source areas. These factors may not necessarily provide a reliable universal qualifier of the WDOH data when attempting to characterize bulk groundwater quality on a very large scale. Without additional water quality data from monitoring wells, or comparative studies that better quantify the relationship between WDOH data and monitoring well data, the nitrate concentration used in the loading calculations should be considered a lower-bound estimate.

For comparative purposes, the water quality concentration estimated using the WDOH data was held against the next largest data set available within the study area. Specifically, the nitrate concentration estimated for Zone 6 using WDOH data (61 data values, geometric mean = 0.65 mg/L, Table 2), was compared to the concentration estimated for the same area using domestic well data reported during a 1989 USGS study (Drost et al., 1998). During that study, a total of 98 domestic wells less than 500 feet deep were sampled by the USGS for nitrate in the Zone 6 area. The geometric mean of that data set is 0.22 mg/L.[3] Nitrate data were also collected from 29 domestic wells within Zone 7 during the USGS study, with a geometric mean of 0.27 mg/L (vs. 18 WDOH wells, geomean = 0.29 mg/L, Table 2). Water quality results obtained from domestic wells may routinely underestimate the concentration of a dissolved constituent for many of the same reasons noted above for large water-supply wells.

The concentration distribution estimated for the study area is similar to what has been historically reported, and what is predicted by recent probability mapping (Tesoriero and Voss, 1997, Drost et al., 1998, Brown and Caldwell, 1985). The zones with the highest estimated concentrations were coincident with areas where population density or land use activity indicate a greater

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[3] The normal reported detection limit for nitrate from the WDOH data was twice that of the USGS data (0.2 vs. 0.1 mg/L). All censored values in both data sets were assumed to be *equal* to the reported detection limit.

likelihood of nitrate loading from the surface to the aquifer system. Additionally, the range of concentrations estimated compare well with the concentrations previously reported for the study area (Tesoriero and Voss, 1997, Drost et al., 1998, Vasey, 1996, Brown and Caldwell, 1985, USGS, 1998, Pearson and Dion, 1979, Vaccaro et al., 1998, Lum and Walters, 1976).

To evaluate the potential impact of underestimating the overall study area nitrate concentration, and to highlight the consequences of rising nitrate levels over time, Table 4 shows the annual nitrate load predicted using alternative bulk study area concentrations of 1, 2, and 3 mg/L. To account for possible reductions in recharge volume over time (due to increasing amounts of impervious surface and sewer facilities, and increasing consumptive use of groundwater) the annual recharge volumes presented in Table 2 were reduced by an additional 5% for the Table 4 calculations.

Table 4. Dissolved Nitrate Loading Estimates – Future Scenarios for Direct Groundwater Discharge to South Puget Sound.

Predicted Bulk Nitrate Concentration of Area of Contribution (mg/L)	Resulting Estimated Annual Nitrate Mass Flux Using Min. Dischrg.[A] (kg/yr)	Resulting Estimated Annual Nitrate Mass Flux Using Max. Dischrg.[B] (kg/yr)
1.0	335,000	421,000
2.0	665,000	845,000
3.0	1,001,000	1,266,000

A – Assumes an additional 5% reduction in the minimum annual groundwater recharge Volume estimated in Table 2.

B – Assumes an additional 5% reduction in the maximum annual groundwater recharge Volume Estimated in Table 2.

Accuracy of Mass Flux Estimates

The estimates of annual mass flux of dissolved nitrate to South Sound via direct groundwater discharge should be considered approximations. While the discharge volume estimates are considered reasonable, the assumptions regarding the behavior of nitrate in the subsurface are judged to bias the load estimates high. In contrast, uncertainties about the water quality database used for the study suggest that the concentration values used to calculate loading may underestimate current conditions. Based on available data, a lower-bound estimate of approximately 160,000-190,000 $kg_{nitrate}$/yr is predicted to be input to South Sound via direct groundwater discharge. However, an increase in the bulk study area nitrate concentration to only 1.0 mg/L results in a predicted input of as high as approximately 300,000-400,000 $kg_{nitrate}$/yr (Table 4). The estimates presented do not account for seasonal fluctuations in discharge volume or water quality. Data are not available to provide reliable estimates of groundwater discharge on a monthly or seasonal basis. Discharge of groundwater from seepage faces above sea level is likely to occur predominantly during the October to May wet season; submarine groundwater discharge rates are likely to be comparatively constant.

Summary and Conclusions

Using available data, an estimate of the annual nutrient load transported to South Puget Sound via direct groundwater discharge was developed for the Ecology South Puget Sound Nutrient Model Study project. Dissolved nitrate was selected as the target compound for the evaluation. An area directly contributing groundwater discharge to the South Puget Sound was first delineated. A simplistic water budget approach was then used to estimate the annual volume of discharge for 19 distinct zones within the area of contribution. An estimate of annual underflow for the Nisqually River alluvial aquifer was also developed. The WDOH public water-supply system database was queried to develop a representative bulk nitrate concentration for each of these areas. The discharge volumes and zone concentrations were integrated to estimate an annual nitrate load to the South Puget Sound.

The loading calculations predict an annual mass of approximately 160,000 to 190,000 $kg_{nitrate}$/yr transported to the South Puget Sound via groundwater discharge. Unit values for nitrate transport as a function of shoreline length and zone area were also estimated. All of the values presented were calculated using a number of simplifying assumptions regarding groundwater movement and chemical behavior in the subsurface. Due to concerns about the representativeness of the water quality data used to estimate bulk concentration, the load estimates may best define the lower-bound of current conditions. To examine the consequences of rising nitrate concentrations in the study area groundwater over time, or under-predicting current conditions, estimates of annual load were also developed using bulk study area nitrate concentrations of 1,2 and 3 mg/L.

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Contacts

Charles F. Pitz	Washington State Department of Ecology Environmental Assessment Program (360) 407-6775

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