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Relationship between Land Use and Nitrate Concentrations in Washington State Department of Ecology Monitored Watersheds

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Technical Memorandum

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Executive Summary

This study provides a method to estimate the level of nitrate export to surface and ground water associated with a variety of sources including: precipitation, animal wastes (rangeland, dairy, and poultry-derived), municipal and on-site wastewater, urban runoff, and agriculturally applied fertilizers, among others. Net annual export coefficients and other loading methods were first developed for each of these primary sources (p. 15) and then applied to 47 monitored watersheds throughout Washington State. The Washington State Department of Ecology has conducted long-term routine water quality monitoring for each of these catchments providing a foundation to assess method accuracy. The methods proved reasonably accurate with a median percent difference between actual and estimated of +4% and -11% for western and eastern Washington located catchments, respectively (p. 37).

By design, this study's nitrate loading methods are simple however an outcome of the analysis was the realization that watershed specific characteristics must be considered to improve accuracy. These considerations can be quite varied from accounting for nitrate attenuation within lakes and reservoirs to understanding the extent of subsurface drainage collection systems, among others.

While the primary study focus was on examining net annual nitrate export levels in surface water, this study also examined the fraction of that export derived from groundwater discharge (p. 53). On a catchment scale, empirical relationships were determined between the net land surface nitrate load level and its effect on underlying groundwater concentrations (p. 60).

These various nitrate loading methods were then applied to the Yakima River, Crab Creek, Nooksack River, and Sumas River watersheds (p. 74 for Yakima, Appendix E for others). The analysis conducted for these case studies was applied at a finer spatial scale and examined the sequential change in nitrate loading over the surface water flow path from headwaters to outlet. In addition, the impact of land surface nitrate loading and its effect on underlying groundwater concentrations was examined within each watershed.

A watershed classification scheme, based on a common seasonal response between flow and the concentration of nitrate, is presented (Appendix C). Based on this scheme, and the annual precipitation and loading estimates specific to the individual watershed, monthly median flows, nitrate yields and concentrations can be derived (Appendix D). This information can be used to assess how loading changes affect median monthly concentrations, among other applications.

In total, these nitrate analysis methods provide a means to assess risk based on the type and intensity of a variety of land use activities to adversely impact surface and groundwater throughout Washington State.

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Introduction

The relationship between land use and it effect on surface and ground water nitrate concentrations is examined for several watersheds in Washington State. Export loading coefficients are determined for a variety of land uses and activities that yield nitrate to surface waters including: precipitation, animal wastes (rangeland, dairy, and poultry-derived), municipal and on-site wastewater, urban runoff, and agriculturally applied fertilizers, among others. Nitrate was chosen for this analysis, in particular, among other water quality parameters, due to its variety of sources and complex pathways and that its concentration in surface and ground waters provides an indication of overall impacts associated with point and nonpoint sources of pollution.

Purposely, the analysis methods applied here are relatively simple, much of it based on monthly or annual perspectives. The emphasis of this work is to provide a method to identify potential pollution concerns in drainages where an understanding of surface water or groundwater nitrate concentrations is limited though where impacts are present. And, importantly, an understanding of the proportional source contributions within a watershed, based on the intensity and proximity of various land use types is required to optimally apply best management practices to improve water quality. This study's land use specific nitrate loading coefficients can therefore also serve as a baseline from which the successful implementation of best management practices can be judged.

Nitrate sources and pathways

The nitrogen (N) atom forms a fundamental building block for all life providing the basis for catalysts, proteins, and amino acids among other vital chemical structures. It is among the most common elements on earth comprising approximately 78% of the atmosphere and yet its availability for organic growth is limited. This is because in its elemental form, as N_2 gas, its atoms are joined with a triple bond requiring considerable energy to break and begin the progression to molecular forms of nitrogen that can be assimilated by plants and animals for growth.

Various natural processes, for example, lightning or volcanic eruptions can facilitate the oxidation of elemental nitrogen to nitrate (NO_3^-) and other useful forms. But much more common, and important on a global scale, is the bacterial-induced fixation of elemental nitrogen (N_2 to NH_3^- and eventually to NO_3^-) within the soil matrix, overcoming the bond strength through the use of catalysts. Fixation refers to the process where nitrogen is incorporated into a molecular form that can be utilized by plants and animals (it must be combined with hydrogen and oxygen before it can be used by plants and animals). Soybean, alfalfa, and red alder are examples of plants that have a commensal relationship with bacterial nitrogen-fixers (rhizobia). The reverse process is referred to as de-nitrification, also a bacterial driven process, where nitrate (NO_3^-) is converted into N_2 gas and recycled back to the atmosphere. De-nitrification requires an anaerobic environment with adequate sources of carbon. Such environments occur at the shallow water table interface, riparian zones of rivers and within the sediments of wetlands and lakes (and agricultural manure lagoons). On a global scale, until the early 20th century, there was a natural balance between nitrogen fixation and de-nitrification. Big changes occurred to this balance in the early 20th century with the increased combustion of fossil fuels and, in particular, the discovery and eventual large scale application of an industrial process which allowed the artificial synthesis of ammonia (Faber-Bosch) from molecular N (N_2), providing a base for plant fertilizers.

There was an early recognition that supplementing soil nitrogen with additional sources – organic fertilizers in the form of manure or guano or through fallow rotation with nitrogen fixing legumes allowed for increased crop yields. The direct application of ammonia-based synthetic fertilizers now allows humans to circumvent bacterial and nutrient recycling processes to augment soil nitrogen. Globally, the increased availability and application of nitrogen-based fertilizers has greatly increased crop yields, providing food for an expanding human population. Concurrently, the energy needs of an expanding population have been met through the extraction and combustion of fossil fuels. Both developments have significantly altered the distribution of nitrogen within the environment.

Nitrogen contained in fossil fuels (coal and oil in particular) have, until relatively recently, been largely removed from a connection to the atmosphere and biosphere. Globally, its expanded mining and combustion from the 20th and into the 21st century has provided a new major source of nitrogen. In addition, the wide spread application of nitrogen-based fertilizers has increased the reservoirs of nitrogen contained within the soil matrix, groundwater, and surface water. Together these new supply pathways have resulted in a significant imbalance in the reactive forms of nitrogen, such as ammonia and nitrate, leading to major environmental impacts. Not only are impacts associated with its increased supply but reactive forms of nitrogen can also move relatively unrestricted within the environment; moving through a flow continuum from groundwater to surface water to eventual discharge to coastal marine waters, resulting in adverse environmental impacts with each transition. This nitrogen-form imbalance from inert gas to reactive forms, its movement between the atmosphere, biosphere, and hydrosphere, and its associated environmental impacts are collectively referred to as the nitrogen cascade (Galloway, 2003).

Global estimates of reactive nitrogen (ammonia, nitrate) production in 2000 was $158 * 10^9$ kilograms; of that total 21% was estimated to come from the cultivation of legumes, 16% from fossil fuel combustion, and 63% associated with the Haber-Bosch process (Galloway, 2003). Of the 63%, 85% of the reactive nitrogen generated by the Haber-Bosch process is associated with fertilizer production, therefore comprising about 54% of the total annual reactive nitrogen production. This has significant environmental repercussions because nitrogen-based fertilizers are almost entirely discharged to the environment either at the point of application associated with direct surface runoff or infiltration to groundwater or, ultimately, associated with wastewater discharge. These supply pathways, depending on their intensity, lead to varying levels of environmental disturbance.

The burning of fossil fuels has contributed to ozone depletion, climate change, and acidification of surface waters. The increase in the supply of reactive nitrogen has resulted in groundwater contamination, limiting its viability as a drinking water source. In the state of Washington groundwater nitrate concentrations exceed the maximum contaminant level for drinking water in encompassing extensive areas of the Crab Creek, Nooksack and Yakima River watersheds, among other locations. Elevated nutrient levels discharged to surface waters disrupts the balance of properly functioning aquatic ecosystems, favoring primary production (algal growth) to a level that compromises oxygen levels, depleting viable habitat for the majority of the organisms previously represented. This occurs on varying scales from river eutrophic zones situated below in-land municipal wastewater discharge locations to massive “dead zones” in marine waters. Routinely, wide expanses of the Great Lakes and the Gulf of Mexico are now devoid of oxygen a condition associated with agricultural-applied fertilizer runoff. The increased supply of nitrogen has led to massive algal growth and its subsequent die-off and decomposition now results in this huge scale of oxygen depletion.

The intensity of reactive nitrogen sources is an important factor to consider in assessing environmental impact. For instance, in the United States and globally, there is an increasing trend of human migration to coastal cities resulting in concentrating waste discharge to marine waters. (Nitrogen tends to be a limiting nutrient to algal growth in marine waters.) Similarly, on a watershed scale, municipalities concentrate and discharge wastewater to fixed locations and, depending on the level of dilution achieved, it can have a major effect on near and far-field nitrogen levels. Also, there is an increasing trend in the intensity of both crop and animal production. This has also led to concentrating nitrogen loading within the environment. Waste-ponds associated with dairies and cattle feedlots are examples of concentrated, high waste-loading situations. Prior practices utilized larger pasture areas for forage and waste assimilation. Now, the application of nitrogen-based fertilizers allows for off-site hay production, supplanting the former relationship between pasture area and the number of animals it could support. The large-scale production of a single crop, depending on its fertilization requirements, increases the risk of environmental impact in comparison to smaller-scale, varied crop production.

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Methods

The metric used to describe the nitrogen loading intensity in this report is yield or the mass of nitrogen introduced per area over a defined period, typically in units of kilograms per square kilometer per year (kg/km^2-yr). A net yield of reactive nitrogen will first be established for each of the major sources typically encountered in Washington watersheds. The reactive forms of nitrogen typically encountered are ammonia and nitrate and together are referred to as dissolved inorganic nitrogen (DIN). While ammonia concentrations were always considered in this analysis, for all but the most polluted surface waters, its levels tend to be at the point of detection. Instead, the major form of reactive nitrogen in flowing surface water and groundwater is nitrate. (Precipitation is an exception and does have a significant representation of ammonia.) Therefore, for simplicity, this report will only refer to nitrate. The net yield is the level exiting a watershed, by surface flow, having already undergone various attenuation processes encountered along its multiple flow pathways. These source-specific yields are referred to as export coefficients. (Other methods were used in this analysis to describe the nitrate export associated with animal production.) Together, these methods were evaluated for their accuracy in characterizing the total net nitrate yield for 47 drainage areas in Washington. In the process, nitrate source types and their relative influence on affecting the net surface outflow yields were evaluated. The analysis was then extended to examine the relationship between land surface nitrate loading and underlying groundwater concentrations. Finally, the full suite of methods was applied to four additional watersheds though at a finer spatial resolution.

This section describes the initial analysis processes including: how the water quality monitoring stations were selected, what data sources were accessed, and the analysis methods applied to these datasets.

Selection of monitoring stations

The main source of water quality data for this work is the Washington State Department of Ecology's (Ecology) long-term routine monitoring station data sets (http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html#4). The monitoring stations tend to be located at the outlets of the major watersheds throughout the state providing coverage of the state's physical, environmental, and land use diversity. For this analysis, a subset of Ecology's monitoring stations was selected based on having a relatively long-term dataset with at least ten or more years of monthly data collection. In addition, only data collected since 1985 was used to reflect a more "current" landscape and adjust for recent laboratory methods and data collection practices. Based on these criteria, 47 watersheds were chosen for inclusion: 29 of the watersheds located in western Washington and 18 on the state's eastside with the division being the Cascade Mountain divide (Figure 1). Table B-1 in Appendix B lists the monitoring station names, locations, and period of data record.

Figure 1. Study monitoring locations and associated watersheds within Washington State.

Monitoring data

Water quality data collected at Ecology's routine monitoring stations include: flow, conductivity, nitrate, ammonia, total and soluble reactive phosphorus, turbidity, total suspended solids, and fecal coliform bacteria. Sampling occurs monthly and while not specifically targeting storm-events, due to the extended monitoring period, storm-events tend to be a part of the data record. However, the data when examined cumulatively, the approach of this analysis, reflects average seasonal variation in flow and water quality.

Following the selection of monitoring stations that met the data criteria, the datasets for each station were sorted by month of collection. For each station, by month, percentiles were then generated for all of the water quality parameters. Emphasis of the initial data analysis was on understanding seasonal patterns in flow and nitrate concentrations characteristic of each watershed and, in the process, finding commonality among the stations, if possible, as well as distinguishing regional patterns. (The analysis that examined watershed patterns in flow and nitrate levels is included in Appendix C.) In addition, the monthly parameter percentiles generated were compared among the monitoring stations to distinguish the range and magnitude of nitrate concentrations, providing a first cut at identifying watersheds with chronically high nitrate levels, as well as those approaching expected background levels; differences that could ultimately be related to the various land uses and activities present, and the nitrate loads they generate.

Median monthly nitrate loads were determined at each station by multiplying the median monthly discharge level, from the data record, by the associated median monthly concentration. The sum of the monthly loads resulted in an overall median annual total (reported in units of kilograms per year – kg/yr). Other loading methods were examined but the study method was selected based on its simplicity and, because it is based on relatively long-term seasonal median levels, was found to be the most appropriate for the determination of export coefficients.

For each station, the annual nitrate load was divided by its drainage area resulting in an annual nitrate yield (reported in units of kilograms per square kilometer per year – kg/km^2-yr). For comparative purposes, the yield is the metric most relevant because it adjusts the annual load for differences in watershed size. The nitrate yield is a net outflow from the watershed, having already undergone various attenuation pathways such as de-nitrification.

Geographic information systems analysis

Central to this analysis is the application of geographic information system (GIS) analysis. Various land cover datasets were used to characterize the study watersheds and this analysis relied primarily on the use of the United States Geological Survey's (USGS) 2006 National Land Cover Dataset (NCLD - http://www.mrlc.gov). The NCLD cover provides a standardized categorization of land use, applying 21 different land use types at a 30-meter resolution (Appendix B, Table B-2).

The analysis of the NLCD data applied the following processes:

- The drainage areas above each of the 47 monitoring stations were delineated.
- These drainage area polygons were then used to clip the NCLD grid.
- The percent of the drainage area represented by each of the NCLD-described land uses present were then determined.

Several of the study watersheds extended beyond Washington's border into Idaho and Oregon. For these stations, the 1999 NCLD for Pacific Northwest states was used to supplement the more recent land use data.

Additional GIS-derived data used in the overall analysis includes:

- Population: http://www.ofm.wa.gov/pop/geographic/default.asp
- Elevation metrics: derived from United States Geological Survey national elevation dataset (NED), 10-meter digital elevation model
- Hydrologic metrics: derived from http://waterdata.usgs.gov/wa/nwis/sw
- Municipal wastewater treatment plant discharge (locations, flows, and nitrate levels): https://fortress.wa.gov/ecy/wqreports/public/f?p=110:1:5572310250749957
- Dairy locations: Washington State Department of Agriculture, Dairy Nutrient Management Program
- Agricultural statistics (hay production, cattle, dairy, poultry production): http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Washington/
- Crop fertilization rates: http://www.agcensus.usda.gov/index.php

Overview of Study Watersheds

Brief description land use within study watersheds

Western Washington watersheds

In total, the 34 unique watersheds (13 of the 47 monitoring locations were sub-watersheds) encompass 103,290 km^2, approximately 56% of Washington states' total area. The 22 western Washington watersheds range in size from the Naselle River at 141 square kilometers (km^2) to the Cowlitz River at 6,048 km^2. Of the 12 unique watersheds on the eastside, the smallest was the Entiat at 1,065 km^2 and the largest Crab Creek at 13,000 km^2. Tables 1 and 2 present the percent representation of the various NLCD land uses for the western and eastern Washington study watersheds, respectively.

Referring to Table 1, the combined evergreen/mixed forest/transitional forest-land designations dominate the land use for the western Washington watersheds comprising between 54% (Samish) to 92% (Humptulips) of their total area. As discussed in detail later in this report, the evergreen forest designation is considered a background condition in terms of nitrate export. These large levels of representation are a primary reason why many of the western Washington watersheds have relatively low surface and groundwater nitrate levels. Forest-land tends to be most highly represented in the upper regions of these watersheds where precipitation levels are also greater. Together these conditions tend to buffer, to a large extent, the effects of the nitrate-generating land uses most prominently represented in the lower valleys such as urbanization and agricultural production. Also, in the lower elevations, and most prominently in the coastal watersheds, there is a greater representation of deciduous forests which are comprised, in part, of red alders. Depending on their level of representation, alders can serve as a significant nitrate source due to its association with nitrogen-fixing bacteria. The lower elevation coastal watersheds such as the Willapa and Samish have a deciduous forest representation of 27% and 33%, respectively of their watershed area.

Urbanization, defined by the land uses of low intensity residential and commercial development, has a low level of representation among the study watersheds. It is most prominently represented in the Green River @Tukwila (11% of the watershed area), Deschutes (5%), and Cedar (8%) watersheds.

Though not adequately described by the open water description, many of the watersheds have "main-line" situated reservoirs. It is discussed in more detail later in the report but worth mentioning here is that nitrate flowing into reservoirs is largely "lost" within them through physical, chemical, and biological processes. Therefore, watersheds with reservoirs tend to have relatively low levels of nitrate export relative to their potential level had the reservoir not been present. The western Washington study watersheds with reservoirs include the Cedar, Cowlitz, Elwha, Green, Nisqually, Puyallup, Skagit, and Skokomish.

Agricultural land use in western Washington is defined mainly by the pasture/hay designation because row crops, small grain, and orchards all have relatively low levels of representation.

Pasture/hay is most highly represented in the Deschutes (7% of watershed), Green @Tukwila (6%), Samish (6%), and Willapa (5%). Hay/pasture is a broad land use designation and could include, in addition to actual hay production, such activities as animal production (dairy, cattle, chicken) among other uses. Described in detail later, the level of nitrate export associated with animal production was determined by methods other than that provided by the NLCD grid information.

Eastern Washington watersheds

Whereas the larger nitrate-generating activities and land uses found for the western Washington watersheds are varied with relatively low levels of representation, due to the overall high representation of forest-land, the eastern Washington landscape is more heavily managed, primarily for agricultural production (Table 2). In particular, small grain production, mainly wheat, is highly represented in the Palouse @Hopper (62% of watershed), South Fork (SF) Palouse (84%), Hangman (62%), Walla Walla (50%) and Crab (41%) watersheds. Both evergreen forest and shrub-land are considered representative of background conditions for nitrate generation for eastern Washington and, overall, remain highly represented for many of the watersheds particularly those that drain the eastern slopes of the Cascades. Much of the Wenatchee (76% of watershed area), Yakima (65%), Methow (76%), and Entiat (76%) remain in forest cover primarily in the upper regions of the watershed. Deciduous forest cover is largely absent though shrub-land emerges as a more dominant landscape feature in eastern Washington.

Similar to the western Washington watersheds, the lower valleys are where greater land alteration occurs and, therefore, where the greatest nitrate generating activities occur for the eastern Washington watersheds. Row crops are represented, though to a relatively low level, at 2% of the watershed area in both the Walla Walla and Crab Creek watersheds. Orchards are represented in the Wenatchee (1% of watershed area) and Yakima (3%). Urbanization is most prominent in the Spokane (6%), SF Palouse (5%), Little Spokane (4%) and Hangman (3%). Portions of the Spokane, Little Spokane, and Hangman watersheds are situated within the greater city of Spokane. The town of Pullman is located within the SF Palouse. Eastern watersheds with storage in the form of lakes or reservoirs include: Crab, Spokane, Wenatchee, and the Yakima.

Table 1. Percent representation of NLCD land uses, western Washington watersheds.

Monitoring Station	Drainage Area (km^2)	Open Water	Perennial Ice/Snow	Low Intensity Residential	Commercial/Industrial	Bare Rock/Sand/Clay	Evergreen / Mixed / Transitional	Deciduous Forest	Shrub-land	Orchards/Vineyards/Other	Grasslands/Herbaceous	Pasture/Hay	Row Crops	Small Grains / Fallow	Woody Wetlands	Emergent Herbaceous Wetlands
Cedar @Logan	482	1.9	==	5.6	1.6	0.2	79.3	6.9	2.2	==	1.3	0.5	==	==	0.1	==
Chehalis @Dryad	476	0.1	==	0.2	0.1	==	81.7	15.5	0.3	==	==	1.8	0.2	==	0.1	==
Cowlitz @Kelso	6,048	1.7	0.6	0.3	0.3	2.6	76.0	10.4	2.8	==	1.2	3.4	0.4	0.1	0.2	==
Deschutes @E St. Bridge	416	0.8	==	4.0	1.4	==	66.2	15.1	1.9	0.5	2.0	6.5	0.1	==	0.7	==
EF Lewis nr Dollar Corner	394	0.2	==	0.7	0.2	0.1	76.2	14.1	2.0	==	4.0	2.0	0.1	0.1	0.2	==
Elwha nr Port Angles	751	0.4	0.6	==	==	6.0	86.3	2.1	2.1	==	2.3	==	==	==	==	==
Green @Kanaskat	608	0.8	==	==	0.1	0.4	90.9	4.3	1.7	==	1.8	==	==	==	==	==
Green @Tukwila	1,212	1.3	==	7.0	4.3	0.3	67.1	7.9	3.0	0.1	1.9	6.0	0.1	0.2	0.2	==
Hoh @DNR Campground	639	0.8	3.3	==	==	5.5	81.8	4.9	1.8	==	1.6	0.1	==	==	0.2	==
Humptulips nr Humptulips	344	0.4	===	==	==	==	91.9	6.6	0.4	==	0.2	0.3	==	==	0.2	==
Kalama nr Kalama	524	0.5	==	==	0.1	0.8	78.9	18.9	0.4	==	0.1	0.1	==	==	==	==
Naselle nr Naselle	141	==	==	==	==	==	81.2	18.6	0.1	==	==	===	==	==	0.1	==
NF Stillaguamish @Ciscero	660	0.4	0.2	0.1	0.1	1.9	83.3	9.0	1.3	==	1.7	1.9	==	==	==	==
NF Stillaguamish @Darrington	213	0.2	0.1	==	0.1	2.3	83.2	9.5	1.5	==	2.5	0.7	==	==	0.1	==
Nisqually @Nisqually	1,828	1.3	1.2	1.1	0.5	1.2	74.3	11.7	1.6	0.5	2.3	3.7	0.2	==	0.5	==
Nooksack @ N Cedarville	1,520	0.6	4.2	0.1	0.1	3.9	74.3	9.2	2.4	0.1	2.4	1.5	0.1	==	0.2	0.1
Puyallup @Meridian St.	2,473	1.3	2.5	2.4	1.2	3.4	76.0	5.2	2.1	0.2	2.0	3.1	0.3	==	0.1	==
Samish nr Burlington	223	1.6	==	1.4	0.6	==	54.1	33.2	1.6	0.1	0.7	5.9	0.2	0.1	0.4	==
SF Stillaguamish @Arlington	648	0.6	0.1	0.7	0.2	1.4	84.9	7.3	1.9	==	2.1	0.7	==	==	0.1	==
SF Stillaguamish @Granite Falls	309	0.7	0.1	0.1	0.1	2.5	87.6	3.5	2.3	==	3.2	==	==	==	0.1	==
Skagit @Marblemount	3,007	2.0	3.8	==	0.1	10.5	65.1	2.3	8.2	==	8.1	==	==	==	==	==
Skagit nr Mount Vernon	6,931	1.8	3.1	0.2	0.1	7.9	68.6	5.6	5.8	==	5.6	1.0	0.1	0.1	0.1	==
Skokomish nr Potlash	592	3.0	==	0.1	0.1	0.6	86.1	5.6	2.2	==	1.6	0.7	==	==	0.2	==
Skykomish @Monroe	1,982	1.4	0.5	0.3	0.1	3.6	80.2	4.8	4.2	==	4.5	0.5	==	==	0.1	==
Snohomish @Snohomish	4,419	1.5	0.3	1.4	0.5	2.5	76.4	7.4	3.3	==	3.6	2.4	0.2	0.1	0.2	==
Snoqualmie nr Monroe	1,780	1.5	0.1	0.9	0.5	2.0	78.7	6.6	2.7	0.1	3.6	2.5	0.2	0.1	0.2	==
Snoqualmie @Snoqualmie	949	1.4	0.2	0.6	0.4	3.5	80.4	3.6	3.5	==	5.9	0.2	==	==	0.1	==
Stillaguamish nr Silvannia	1,454	0.8	0.1	0.6	0.2	1.5	81.2	9.6	1.6	==	1.8	2.5	0.1	0.1	0.1	==
Willapa nr Willapa	339	0.4	===	===	0.2	===	67.1	27.3	0.3	==	0.1	4.5	==	==	0.2	==

Table 2. Percent representation of NLCD land uses, eastern Washington watersheds.

Monitoring Station	Drainage Area (km^2)	Open Water	Perennial Ice/Snow	Low Intensity Residential	Commercial/Industrial	Bare Rock/Sand/Clay	Evergreen / Mixed / Transitional	Deciduous Forest	Shrub-land	Orchards/Vineyards/Other	Grasslands/Herbaceous	Pasture/Hay	Row Crops	Small Grains / Fallow	Woody Wetlands	Emergent Herbaceous Wetlands
Crab nr Beverley	6,048	2.4	==	0.4	1.3	==	0.5	==	38.6	0.3	5.3	8.0	1.6	41.2	0.1	0.4
Entiat nr Entiat	1,065	0.2	0.2	===	0.1	3.1	67.7	0.6	8.4	0.4	18.0	==	==	==	==	==
Hangman @mouth	1,776	0.3	==	1.5	1.5	0.1	19.4	0.1	8.1	==	4.8	==	==	62.0	==	0.1
L Spokane nr moutn	1,742	0.9	==	3.0	1.4	0.1	53.5	0.2	6.8	==	4.9	13.1	0.5	9.7	0.2	0.1
Methow @Pateros	4,643	0.4	==	0.1	0.2	3.0	65.1	0.4	10.6	0.5	18.6	0.3	==	==	0.1	==
Methow @Twisp	3,261	0.4	0.1	==	0.2	3.7	69.0	0.5	8.9	0.3	15.6	0.3	==	==	0.1	==
Palouse @Hopper	8,818	0.6	==	0.5	0.9	==	10.3	0.1	21.4	==	2.6	==	==	62.0	0.1	0.2
Palouse @Palouse	888	0.2	==	0.4	0.6	0.2	58.9	0.1	2.9	==	0.3	0.1	==	29.7	==	==
SF Palouse @Pullman	332	==	==	3.3	2.3	==	6.7	==	3.4	==	0.2	==	==	83.8	==	==
Spokane @Riverside	3,808	1.4	==	4.3	2.2	0.1	35.5	0.1	8.3	0.8	5.8	3.2	==	33.4	0.1	0.1
Tucannon @Powers	1,290	==	==	0.2	0.3	0.2	20.3	0.3	27.6	==	16.0	2.4	==	31.3	==	==
Walla Walla nr Touchet	4,423	0.1	==	1.0	0.6	==	17.0	0.8	17.2	0.9	6.7	3.4	2.0	49.9	==	==
Wenatchee @Leavenworth	1,718	1.3	0.8	===	0.1	6.3	72.8	2.2	5.7	0.1	7.1	0.1	==	==	0.3	==
Wenatchee @Wenatchee	3,434	1.0	0.5	0.2	0.2	5.4	67.8	2.1	7.8	1.4	11.5	0.1	==	==	0.2	==
Yakima nr Cle Elum	643	4.9	==	===	0.6	1.3	66.5	1.0	4.4	==	4.0	0.8	==	==	0.2	==
Yakima @Kiona	15,314	0.8	==	0.9	0.8	1.0	33.7	0.6	31.4	2.5	13.4	5.6	==	6.7	0.1	0.1
Yakima @Nob Hill	8,424	1.2	0.1	0.6	0.6	1.7	49.3	0.5	25.2	1.2	9.2	3.6	==	2.2	0.1	==

Initial examination of nitrate concentrations

Figure 2 provides an overview of the entire nitrate concentration dataset for each of the monitoring locations in the form of box plots. The upper and lower edges of the central box represent the 75th and 25th percentile concentrations, extending beyond the central box are the 90th and 10th percentiles and the dot inside the central box represents the median concentration. In the figure, the stations are ordered by their 90th percentile concentration.

As observed, the eastern Washington monitoring locations have among the highest nitrate concentrations. The eastside's lower rainfall levels result in reduced dilution of point and nonpoint nitrate loading. In the case of Crab Creek and the Yakima River @Kiona, flow management for irrigation, its withdrawal and eventual return to the river, are also important factors influencing concentrations.

The lowest concentrations tend to be associated with watersheds that have a high level of in-line storage either in the form of a lake or reservoir. Both the Spokane River @Stateline and the Wenatchee @Leavenworth are situated below lakes while the Skagit @Marblemount, Cedar @Logan, and Yakima River @Cle Elum are all situated below reservoirs. These watersheds also tend to have a lower range in observed concentrations since the majority of the observed flow originates from a single source/location; largely unaffected by the variation in loading occurring above the reservoir.

Nitrate storage in groundwater also has a role in reducing the range in concentrations. This is most evident when the groundwater has been impacted by infiltration of excessive land surface loading. This situation applies to the Little Spokane, Samish, and Deschutes Rivers. For these watersheds, elevated nitrate surface loading combined with greater surface soil permeability increase the vulnerability of groundwater to contamination.

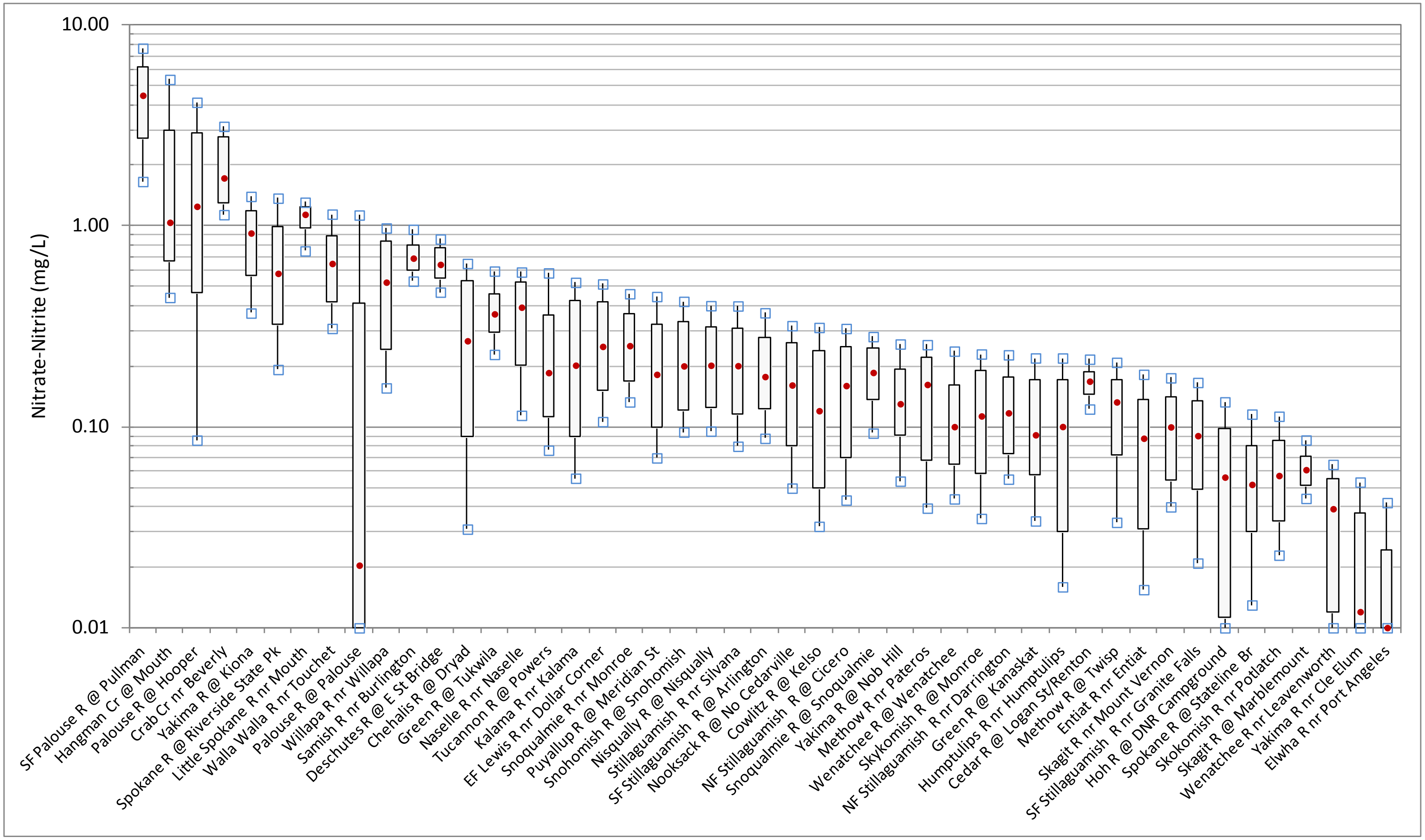

Figure 2. Box plots of nitrate concentrations observed at monitoring locations, sorted by 90th percentile.

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Export Coefficients

This section of the report discusses how nitrate export coefficients were determined for each of the NLCD land use descriptions. Additional methods are presented for source activities affecting nitrate loading not described by the land cover dataset including municipal wastewater treatment plant discharge and commercial animal production. Initially, regionally-based background nitrate export yields were derived for eastern and western Washington situated watersheds. From that information, a natural net level of nitrate loss, or attenuation, was defined. Attenuation is mainly attributed to de-nitrification though could also be attributed to biological uptake or sedimentation among other potential loss or storage pathways. These derived net attenuation levels were central to the overall study in that they were used to determine net nitrate loading yields for the monitored watersheds. It is, therefore, assumed that all nonpoint sources of nitrate undergo similar levels of attenuation regardless of the source, with the level based on the location of the watershed, eastern or western Washington.

The background loading condition

A diagnostic method was initially applied to distinguish, among the monitored watersheds, those that are relatively un-impacted from point and nonpoint sources of nitrate and could, therefore, serve as a reference condition. The method is based on the levels of dissolved inorganic nitrogen (DIN = nitrate + ammonia) measured in precipitation through the National Atmospheric Deposition Program (NADP) http://nadp.sws.uiuc.edu/. The assumption being that DIN loading from precipitation serves as the dominant external source for watersheds relatively un-impacted by point and nonpoint source pollution. Based on the NLCD land use analysis, and the identification of municipal wastewater treatment discharge locations, a number of the water quality monitoring locations were identified as representing relatively un-impacted watersheds from a nitrate loading perspective.

To determine the DIN present in precipitation, data collected from several of the NADP monitoring stations, within Washington and Idaho were examined including: Olympic National Park (Hoh watershed -WA-14), North Cascades at Marblemount (Skagit – WA-19), La Grande (Nisqually – WA-21), Palouse Conservation Farm (Palouse-WA-24), Columbia River Gorge (WA-98), Mount Rainier-Tahoma Woods (Cowlitz-WA-99), Sullivan Lake (WA-15), and Priest River Experimental Forest (ID-02) (Table 3).

The distribution of the rain monitoring stations is not extensive enough within the state to apply a Thiessen polygon-type averaging method to these data. So instead, annual precipitation-weighted DIN concentrations at stations WA-14, WA-19, WA-21, and WA-99 were used to represent western Washington levels while the overall average of stations WA-24, WA-15, and ID-02 were used to represent eastern Washington.

Distinct differences are present in the DIN concentrations among these stations with the greatest distinguishing factor being location. The western Washington stations were found to have an overall average DIN concentration of 0.253 milligrams per liter (mg/L) DIN while levels observed for the eastern Washington stations were approximately two times greater with an average concentration of 0.574 mg/L. For this reason, the routine water quality monitoring stations were divided into two groups based on whether they are situated east or west of the Cascade divide. This eastern / western division is fundamental to all further calculations presented in this analysis.

Table 3. Average precipitation nitrate concentrations and yields observed at NADP monitoring locations within greater study area.

Station	Description	Proximity	Location – Lat. / Long.	Elevation (m)	Avg. DIN Concentration (mg/L)	Avg. DIN Yield (kg/km^2-yr)	N (years)
WA-14	Olympic National Park – Hoh Ranger Station	Western	47.8597 -123.9325	182	0.105±0.023	322±96	29 (1980-2008)
WA-19	North Cascades National Park – Marblemount Ranger Station	Western	48.5403 -121.446	124	0.320±0.055	633±134	30 (1984-2013)
WA-21	La Grande	Western	46.8353 -122.2867	617	0.356±0.092	343±79	30 (1984-2013)
WA-99	Mount Rainier National Park – Tahoma Woods	Western	46.7582 -122.1243	424	0.214±0.042	275±68	15 (1999-2013)
WA-98	Columbia River Gorge	Eastern	45.5697 -122.210	233	0.395±0.069	564±124	12 (2002-2013)
WA-24	Palouse Conservation Farm	Eastern	46.7606 -117.1847	766	0.596±0.104	291±59	29 (1985-2013)
WA-15	Sullivan Lake	Eastern	48.8433 -117.2839	796	0.510±0.144	264±72	4 (1984-1987)
ID-02	Priest River Experimental Forest	Eastern	48.3518 -116.8397	726	0.539±0.068	413±46	11 (2003-2013)

The shortcoming of this approach is that there are transitional zones such as the coastal and the eastern slope Cascade watersheds where precipitation DIN levels are likely lower than these regional averages. However, as it will be presented, the approach proved adequate in describing background nitrate loading conditions for the majority of the monitoring stations examined. Also, these concentrations serve as a baseline type expectation for DIN in precipitation as a consequence of the overall changes to the global nitrogen cycle, not a true reflection of background conditions.

Forest / Shrub-land export

Among the study watersheds, those situated in eastern Washington identified as relatively un-impacted from excessive nitrate loading include the Entiat, Methow (Twisp), and Tucannon. (Watersheds that have significant levels of surface water storage were not included in this assessment due to the complicating factor of nitrogen loss within the water body.) Western Washington watersheds identified as representing background DIN loading conditions include the Hoh, Humptulips, North Fork Stillaguamish (Darrington), and the Skykomish watersheds.

For western Washington, the watersheds identified as representative of background-type conditions were those with a higher representation of forestry-based designations of evergreen forest as opposed to transitional (disturbed forest-lands) or deciduous designations. As observed from Table 4, for the western Washington watersheds, forest-lands represent the major land use with up to a 99% presence for the Humptulips. (Lands designated as shrub-land were included along with forest-lands as representative of background-type landscapes particularly for eastern watersheds where it is more prominent.)

In western Washington, trees designated deciduous are primarily represented by alders and maples. Bacteria associated with roots of red alders (*Alnus rubra*) are nitrogen-fixers and provide an additional and, in some cases, significant influence on stream nitrate concentrations. Alders are often highly represented along riparian zones at lower elevations, due to disturbance, and provide a direct nitrate source to the adjacent surface waters. So the ideal western Washington watershed representing background conditions has the majority of its land cover as forest-land with the greatest representation evergreen and relatively low levels of deciduous forest. These characteristics are best represented by the Hoh, Skykomish, and Humptulips watersheds and, to a lesser degree, the North Fork Stillaguamish.

Several of these watersheds contain point source discharges in addition to land uses associated with nitrate-generating activities; none can be considered truly pristine. What they all have in common is that the DIN load associated with these additional nitrate-generating activities is proportionally small in comparison to the estimated background or precipitation-based load.

Table 4. The representation of NLCD land uses within background watersheds.

Watersheds – Water Quality Monitoring	Transitional	Deciduous	Mixed Forest	Evergreen	Shrub-land	Grasslands/ Pasture	Sm. Grains/ Fallow	Orchard	Annual WWTP Flow (% of total)	Dairy (no.)	Bare Rock	Perennial Ice	Open Water	**Total Representation**
Entiat nr Entiat	1.22	0.55	0.79	66.88	8.44	18.03	===	0.44	===	===	3.14	0.20	0.16	99.85
Methow @Twisp	0.96	0.49	1.20	67.75	8.94	15.87	0.02	0.33	0.02	===	3.73	0.06	0.36	99.71
Methow @Pateros	0.70	0.43	1.21	63.94	10.56	18.86	0.09	0.46	0.05	===	3.04	0.04	0.37	99.70
Tucannon @Powers	1.46	0.25	1.60	18.65	27.61	18.37	31.29	===	0.20	===	0.24	===	0.03	99.50
Hoh @DNR Camp.	3.98	4.88	2.93	74.91	1.81	1.70	===	===	===	===	5.47	3.26	0.81	99.75
Humptulips nr Humptulips	8.04	6.57	4.21	79.67	0.35	0.48	===	===	===	===	0.02	===	0.43	99.77
NF Stillaguamish @Darrington	8.96	9.47	7.53	66.70	1.46	3.18	0.01	===	===	===	2.30	0.05	0.15	99.81
Skykomish @Monroe	3.15	4.76	3.28	73.67	4.17	5.02	0.02	0.01	0.01	2	3.61	0.45	1.37	99.51

Annual precipitation-based DIN loading was calculated by applying the average DIN concentrations, based on regional location (eastern or western Washington), to the average annual precipitation level, specific to each watershed. For watersheds with low levels of point and nonpoint source loading, this precipitation-based loading is the most significant incoming source of nitrogen. As an initial screening method, the annual in-stream nitrate load observed at the water quality monitoring locations was then divided by the precipitation-based DIN load to examine its influence on the overall observed watershed DIN yield. What proportion of the watershed net yield is potentially derived from nitrate contained in precipitation? Water quality monitoring stations representative of relatively un-impacted watersheds (defined by minimal nitrate loading associated with point and nonpoint pollutant sources) were then used to determine an overall precipitation-based DIN net export level. These watersheds then provided an estimate of the net export expected from a background-type condition.

Based on the difference between the total DIN annual net yield (kg/km^2-yr), determined at the routine water quality monitoring stations, and the annual yield associated with precipitation-based nitrate falling directly on the "background" watersheds, approximately 40% is exported from the western Washington watersheds, resulting in a 60% attenuation or loss level (Table 5). In comparison, for eastern Washington's background watersheds, only about 5% of the precipitation-based nitrate load is exported; resulting in a 95% attenuation level. A primary factor in the net attenuation differences between eastern and western Washington watersheds is due to differences in the net outflow yield; a function of differing overall precipitation and evapo-transpiration rates.

Table 5. Surface outflow and precipitation-based nitrate yields and their ratios at background monitoring locations.

Station	Net DIN Yield (kg/km^2-yr) @ monitoring location	DIN Yield (kg/km^2-yr) precipitation-based	DIN Load Ratio river:precipitation
Entiat nr Entiat	16	627	0.03
Methow @Twisp	23	465	0.05
Methow @Pateros	19	428	0.04
Tucannon @Powers	22	271	0.08
Eastern Washington Median	**21**	**447**	**0.05**
Hoh @DNR Camp.	216	850	0.25
Humptulips nr Humptulips	361	807	0.45
NF Stillaguamish@Darrington	240	665	0.36
Skykomish @Monroe	292	698	0.42
Western Washington Median	**266**	**752**	**0.39**

These attenuation levels are a central finding in this analysis and were applied to the other nitrate sources to determine net export coefficients. This assumes these regional net attenuation levels apply equivalently regardless of nitrate source (municipal wastewater point source discharge was the exception to this assumption), setting a base level of attenuation. Also, the net attenuation from these background watersheds is primarily occurring within the greater groundwater-stream-river channel network and could, therefore, be extrapolated to other watersheds with more varied nitrogen sources. In reality, net attenuation rates vary, likely significantly, by source and flow pathway. The type of nitrogen source and a watershed's unique physical (size, hydraulics, storage) and biological characteristics (riparian and wetlands interaction) are among the complex of factors affecting it. Some of these differences, as it will be discussed later, were accounted for. However, while acknowledging this complexity, as it will be presented later, these general attenuation levels provide a relatively good approximation of background net losses.

On average, for the background stations, results indicate that the annual net DIN yield for western Washington watersheds is about 266 kg DIN/km^2-yr with the yield for the eastside watersheds, 21 kg/km^2-yr. These background yields establish the two regional levels and a baseline from which to assess whether, among the other stations, their current net DIN yields, based on monitoring, are substantially above this level, indicating point and nonpoint source impacts.

Deciduous forest

The percent of the watershed with deciduous tree cover is provided in Figure 3. As observed, deciduous tree cover has an insignificant level of representation for the majority of the eastern Washington watersheds. Instead, it is prominently represented for the majority of the western Washington watersheds and, in particular, the lower elevation coastal watersheds such as the Samish and Willapa.

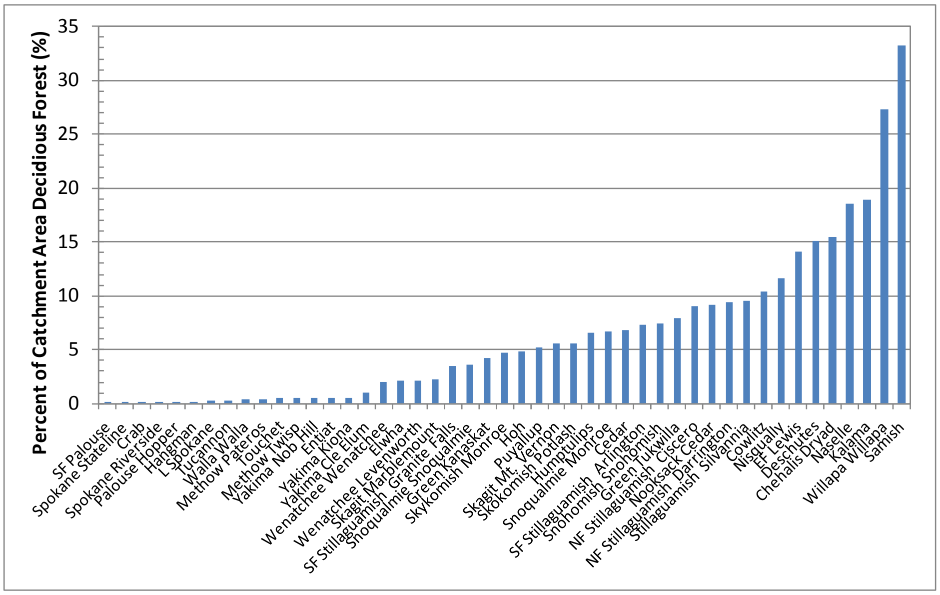

Figure 3.   Percent of watershed comprised of deciduous forest-lands.

Prominent among the deciduous tree species present in western Washington is the red alder (*Alnus rubra*). A commensal bacteria associated with red alder has the ability to fix nitrogen and, depending on factors such as density of alder growth and proximity to surface waters, provides an additional source of nitrate within forest-lands.

Red alder-generated dissolved nitrogen levels in soils have been estimated at between 2,600 and 3,900 kg/km^2-yr (Compton, 2003; Pojar, 1994). Based on these reported yields, and assuming a 40% attenuation level for western Washington, results in a net export nitrate level of between 1,040 and 1,560 kg/km^2-yr attributed to red alders.

The final net export coefficient for deciduous tree cover applied in this analysis was ultimately based on calibration through adjustment of the nitrate export associated with the deciduous tree representation for the coastal (Willapa, Samish, Kalama, and Naselle River) watersheds. This best fit approach resulted in a net nitrate export yield of 1,000 kg/km^2-yr.

The NLCD deciduous tree designation includes species other than alders, for example, broad-leaf maples (*Acer macrophyllum*). For this reason, the net nitrate export level applied here is set at a lower level than what actually occurs if the areal extent of alders had been considered exclusively. The lower nitrate export level applied by this study is appropriate given this limitation.

The net nitrogen export coefficient for deciduous cover in eastern Washington applied the prior forest-land level of 21 kg/km^2-yr since alder presence, among the deciduous species represented, is insignificant.

N fertilization rates for crops

Estimates of net nitrate export coefficients for NLCD land covers: orchards/vineyards, row crops, and small grain (wheat) were based on reported United States Department of Agriculture (USDA) Census nitrogen fertilization rates (http://www.agcensus.usda.gov) for various crop groups (Table 6). All crops with reported annual average nitrogen fertilization rates were considered and grouped according to the appropriate NLCD designation. The overall median of the reported annual fertilization rates was determined for each crop group and the associated net export level for eastern and western Washington was determined by applying the 0.05 (eastern watersheds) and 0.40 (western watersheds) attenuation factors, respectively, along with assumed crop up-take levels.

Row crops

Assumptions used to estimate net nitrogen export levels associated with row crops include:

- Median annual nitrogen fertilizer application rate of 14,024 kg/km^2-yr (125 pounds/acre-year)
- An assumed overall crop nitrogen up-take level of 60% (Sullivan, 1999)
- Attenuation level of 60% for western Washington and 95% for eastern Washington

These assumptions result in an annual net nitrate export level of 2,240 kg/km^2-yr for western Washington and 280 kg/km^2-yr for eastern Washington.

Orchards/Vineyards

Assumptions used to estimate nitrogen export associated with orchards /vineyards include:

- Median annual nitrogen fertilizer application rate of 9,427 kg/km^2-yr (84 pounds/acre)
- An assumed nitrogen up-take level of 50% of applied N
- Attenuation level of 60% for western Washington and 95% for eastern Washington located watersheds.

The application of these assumptions results in a net nitrate export level of approximately 240 kg/km^2-yr for eastern Washington and 1,890 kg/km^2-yr for western Washington.

Table 6. Typical nitrogen fertilizer application rates for various crops prominent in Washington.

Crop	Average N application rate (kg/km^2-yr)	No. Years Reported
Row Crops		
Carrots	20,309	3
Asparagus	13,533	6
Sweet Corn	15,755	3
Potatoes	32,437	13
Peas	5,003	6
Onions	21,709	6
Cucumbers	5,712	1
Beans (snap)	6,888	2
Sugar Beets	9,296	1
Median = Assumed Net Export =	14,024 280 (eastern WA), 2,240 (western WA)	
Orchards / Vineyards		
Grapes		
Apples	6,128	7
Apricots	11,917	5
Cherries	8,941	6
Peaches	10,976	4
Pears	9,427	6
Median = Assumed Net Export =	9,427 240 (eastern WA), 1,890 (western WA)	
Berries		
Blueberries	4,592	1
Raspberries	9,539	6
Strawberries	6,048	5
Median = Assumed Net Export =	6,048 1,210 (western WA)	
Small Grains		
Barley	8,400	2
Wheat (spring)	9,931	3
Wheat (winter)	8,248	14
Median = Assumed Net Export =	8,400 130 (eastern WA), 1,010 (western WA)	

Small grain/fallow

Assumptions used to estimate nitrogen export associated with small grain and fallow designated lands include:

- Median annual nitrogen fertilizer application rate of 8,400 kg/km^2-yr (75 pounds/acre-year)
- Crop nitrogen up-take level of 70% (Sullivan, 1999)
- Attenuation level of 60% for western Washington and 95% for eastern Washington

This land use designation applies mainly to the lower southeast portion of the state (greater Palouse region) specifically the Palouse, Hangman, and Walla-Walla watersheds. Reported nitrogen applications for winter wheat from the USDA National Agricultural Statistics Service database is a median of 8,400 kg/km^2-yr (2009). Of this, approximately 70% is assimilated into plant growth. Assuming equivalent attenuation levels as determined for background sources results in a net level of DIN export of approximately 130 kg/km^2-yr for eastern Washington and 1,010 kg/km^2-yr for western Washington.

Hay/pasture

Many types of land-use activities occur within the hay/pasture land cover designation from small hobby farms in Mason County to large commercial alfalfa operations in Franklin County. Because of the significance and diversity of the nitrate sources represented, and their highly fractured spatial representation, it is a difficult land-use designation to set a characteristic net nitrate export coefficient.

For instance, poultry, dairy, and beef cattle production are all represented within this designation in addition to actual commercial hay production. Poultry production in Washington is mainly based in western Washington, in just a few counties. The dairy industry has a greater geographical distribution represented on both sides of the Cascades but it too is concentrated within just two counties, Whatcom and Yakima, representing about 43% of the state's total. For these reasons, the net level of nitrate generated by dairy, poultry, and beef production occurring within the study watersheds were estimated by other methods. This land cover designation, and the nitrate export associated with it, is based solely on the effect of pasture management and hay production.

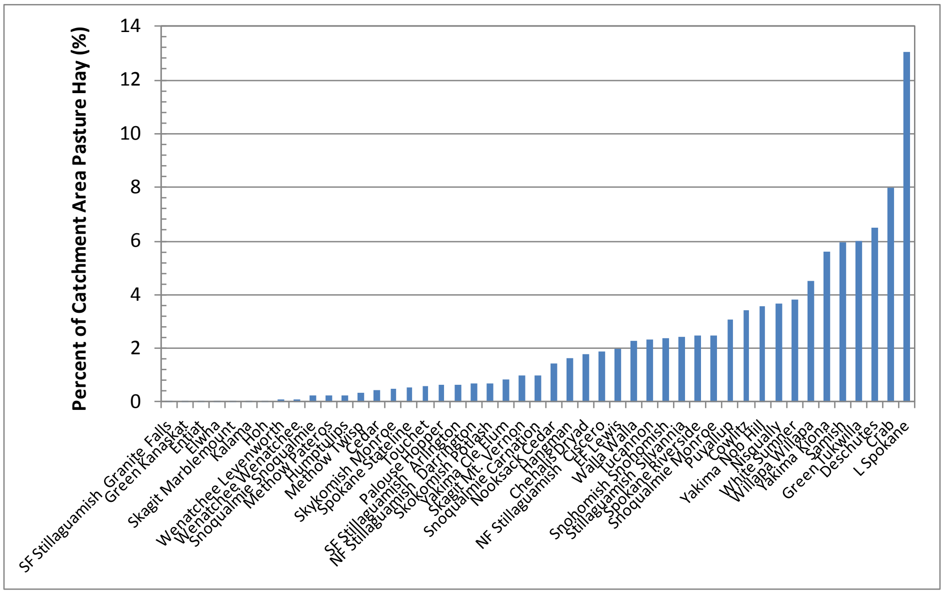

Figure 4. Percent of watershed represented by pasture/hay land use.

The United States Department of Agriculture (USDA) Census reports the annual level of hay harvested (acres), yield per acre, and total tonnage of production for Washington State counties (http://www.nass.usda.gov/Statistics_by_State/Washington/Publications/Annual_Statistical_Bulletin).

The data are divided into two categories: alfalfa and "other" hay. The data used in this analysis is from 2008. Alfalfa production represents approximately 65% of the total commercial hay production in Washington with the majority occurring on the eastside of the state, in particular, Franklin and Grant counties. Alfalfa is a legume (associated with rhizobia) requiring relatively low levels of nitrogen-based fertilization, if any. The "other" hay categorization is more highly represented in western Washington though also includes the economically important Timothy hay production in Kittitas County.

State-wide, from the USDA 2008 data, the average yield for “other” hay is 2.7 tons per acre or about 608,107 kg/km^2. Typical nitrogen content of hay (dry weight) is about 2% (Snyder, 1998). Assuming 70% of the nitrogen-based fertilizer applied is incorporated into cellular growth results, through back calculation, in an average application rate of around 17,400 kg/km^2 (155 lbs/acre). This estimate is close to annual recommended nitrogen fertilization rates for western Washington pastures (Hart, 2000). Based on acres harvested, alfalfa and “other” hay represent 14% and 86%, respectively, of the total hay production in western Washington. While in eastern Washington alfalfa and “other” hay represent 68% and 32%, respectively. It is assumed that the alfalfa nitrogen requirements are negligible and only the “other” hay production requires nitrogen-based fertilization.

The following assumptions were used to estimate net nitrate export coefficients associated with pasture and hay designated lands:

- An annual average nitrogen fertilizer application rate of 17,400 kg/km^2 (155 lbs/acre).
- A 70% up-take level.
- Alfalfa external (fertilizer) nitrogen requirements are negligible.
- Nitrogen-based fertilization occurs solely on “other” hay (as opposed to alfalfa) representing 32% of the pasture-lands in eastern Washington and 86% in western Washington. These levels of representation were used as a weighting-factor to determine regional (east or west) averages.
- In addition to uptake losses, environmental attenuation results in an additional loss level of 95% and 60% for eastern and western watersheds, respectively.

Based on these assumptions, a net nitrate export rate of 80 kg/km^2-yr (eastern Washington) and 1,800 kg/km^2-yr (western Washington) were determined for the hay/pasture land use designation.

Urbanization

The NLCD cover divides urbanization into two levels of residential development: single family (low intensity) and multi-family apartment complexes (high intensity) with an additional urbanization designation, commercial / industrial development (refer to Table B-2 in Appendix B). Each of these is a broad categorization of the urban landscape with numerous potential nitrate sources from automobile and factory emissions to residential fertilization applications, among others. For this reason, assigning a set nitrate export coefficient specific to each group is difficult. In this analysis it is assumed that the major source of nitrate associated with low intensity residential development is the application of nitrogen-based lawn fertilizer.

Suggested nitrogen fertilization rates for residential lawns in Washington is 4 pounds per 1,000-square feet of lawn (~20,000 kg/km^2-yr) (Stahnke, 2005). Homeowner surveys indicate wide ranges in actual annual application rates with average levels about 2.2 pounds per 1,000-square feet (Law, 2004). This study is going to further reduce these levels to an average of 1 pound per

1,000-square feet per residence based on the author's perception of lower overall use of lawn fertilizers, reflecting changing cultural perspectives. A check on this assumption follows.

The average residential lot size is estimated at 0.25 acres (0.001012 km^2) half of which is assumed occupied by structures or hard surfaces (roof, sidewalks, driveways etc). This leaves approximately 0.125 acres (0.0005058 km^2) of lawn area for fertilization. Based on this potential area and the typical application rate of 5,000 kg N/km^2-yr results in an annual residential application rate of 2.5 kg/residence-yr. Typical lots sizes vary particularly between urban, suburban, or rural proximity but it is assumed that regardless of size only about 0.125 acres is actively managed as lawn and fertilized annually. Assuming similar attenuation levels as found for background sources results in a net export associated with residential lawn fertilization of 1.0 kg/residence-yr. and 0.13 kg/residence-yr. for western and eastern Washington residences, respectively. The total number of households present in a watershed is estimated based on an average per capita occupancy rate of 2.5 per house.

Swamp and May Creeks, located in King and Snohomish counties in western Washington, were selected to determine net nitrate export levels associated with the urbanized land use designations. King County Department of Natural Resources has maintained long-term routine water quality monitoring stations at the lower reaches of each creek (http://green.kingcounty.gov/WLR/Waterres/StreamsData/Default.aspx) and these data were used to calculate annual nitrate loads. The representation of the various NLCD categories is presented in Table 7.

The 60 km^2 Swamp Creek drainage is heavily urbanized with low-intensity residential development comprising about 46% (28 km^2) of the watershed and commercial development comprising a further 12% (Table 7). Applying 2010 Census Bureau data for the drainage, the average number of households per square kilometer is 700. Assuming that the majority of the nonpoint source-derived nitrogen migrating to surface waters in the urban designated land use is associated with the application of fertilizers and that the average annual nitrogen application rate is 2.5 kg/household results in a gross nitrate yield of 1,750 kg/km^2. Applying a 60% attenuation level for western Washington results in a net export yield of about 700 kg/km^2-yr.

The NLCD grid does not include any high-intensity residential development within either Swamp or May Creeks simplifying the determination of the net nitrate export of commercial/industrial. Both Swamp and May Creeks are within sewer collection systems and it is assumed that animal production is minimal given both drainages urban setting. Assuming the 700 kg/km^2-yr associated with low intensity development along with the application of the other export coefficients (determined previously), though adjusting the commercial / industrial / transportation coefficient to equate to the observed annual nitrate load results in a net export level of 800 kg/km^2-yr, close to that found for low intensity residential development. These urban nitrate export coefficients, derived for Swamp Creek, were used as input to estimate the annual load for May Creek. These yields resulted in the determination of an annual nitrate load within 3% of the load derived from observed data (Table 7).

Eastern Washington urbanization coefficients were derived by assuming a similar nitrate loading yield ratio between forestry (background) and low intensity and commercial land use designations for western Washington (~3.0) and so were both estimated at 60 kg/km^2-yr.

Table 7. Percent of the Swamp and May Creeks drainage area represented by NLCD land use type.

NLCD Land Use Description	Swamp Creek	May Creek
Drainage Area (km^2)	60*	33
Open Water	0.51	0.72
Perennial Ice/Snow	==	==
Low Intensity Residential	46.38	24.94
High Intensity Residential	==	==
Commercial/Industrial/Transportation	11.79	5.98
Bare Rock/Sand/Clay	0.01	==
Quarries/Strip Mines/Gravel Pits	0.07	==
Transitional	0.24	0.65
Deciduous Forest	15.52	21.77
Evergreen Forest	5.75	20.49
Mixed Forest	9.31	18.90
Shrub-land	5.00	3.29
Orchards/Vineyards/Other	==	0.01
Grasslands/Herbaceous	2.52	1.74
Pasture/Hay	0.01	0.80
Row Crops	==	==
Small Grains	0.06	0.04
Fallow	==	0.01
Urban/Recreational Grasses	2.24	0.05
Woody Wetlands	0.59	0.35
Emergent Herbaceous Wetlands	==	==
Observed Nitrate Load (kg/yr)	448	543
Estimated Nitrate Load (kg/yr)	468	481

*the effective drainage area applied was 43 km^2

Bare rock/sand/clay

Land cover designated as bare rock, sand, or clay were considered a background condition and assumed to have a net export level similar to forest-lands. The area represented by bare rock, sand, or clay (km^2) was multiplied by the average annual precipitation (m) with an assumed DIN concentration of 0.235 mg/L (west-side situated watersheds) or 0.574 mg/L (east-side situated watersheds). It was assumed that the level of attenuation for west-side watersheds is 60% and east-side watersheds, 95%.

Urban grass-lands

The export of nitrate associated with the urban recreational grasses designation is expected to be primarily associated with lawn fertilization so the export coefficient is assumed the same as that determined for low intensity residential development (700 kg/km^2-yr).

Discussion of net nitrate export coefficients

A summary of the net nitrate export coefficients associated with the NLCD land-use types is included in Table 8. The table is divided by watershed location: western and eastern Washington watersheds. Using forest land covers as a reference of the background DIN net export then, in comparison, the urbanized landscape exports nitrogen at a level that is three times greater. This level of increase is important considering that these land use designations comprise a major portion of the Puget Sound lowlands of Pierce, King, and Snohomish counties and drain to Puget Sound.

Table 8. NLCD designations and their assumed net nitrate export yields.

Designation	Net Nitrate Export (kg/km^2-yr)		Comment
	Western	Eastern	
Open water	-5,500	-1,000	Nitrate loss through biological, physical, and chemical processes.
Perennial ice and snow	→		Nitrate loss through "permanent" storage as ice.
<u>Urban landscape</u>			
Low Intensity	700	60	
High Intensity	800	60	
Commercial	800	60	
Bare rock/sand/clay	→		Export assumed at a level equivalent to background (i.e. Forest-land).
Quarries/strip mines/gravel pits	===	===	Assumed negligible within scale analyzed
<u>Forestry</u>			The level of forest-land export is set based on an average nitrate level present in precipitation (0.253 mg/L Westside, 0.574 mg/L eastside) with a net export level of 40% for Westside and 0.05% for eastside watersheds.
Transitional	266	21	
Evergreen	266	21	
Mixed forest	266	21	
Deciduous	1,000	21	
Shrub-land	266	11	West-side shrub land export level same rate as forest-lands. (This land use has a relatively low presence on the Westside.)
Orchards/Vineyards	1,890	240	Based on USDA Census reporting
Grass-lands	265	50	
Pasture/Hay	1,800	80	Based on USDA Census reporting
Row crops	2,240	280	Based on USDA Census reporting
Small grains / Fallow	1,010	130	Based on USDA Census reporting
Urban recreational grasses	700	30	Assumed similar to low intensity residential
Woody wetlands	===	===	Assumed negligible within scale analyzed
Emergent wetlands	===	===	Assumed negligible within scale analyzed

Except for the cities of Yakima, Wenatchee, and Spokane, much of eastern Washington has relatively low levels of urbanization. Instead, nitrate loading to surface waters is primarily associated with agricultural production. (Nitrate export from animal production is presented in the following section.) The application of nitrogen-based fertilizers associated with orchard/vineyard, row crops, hay, and wheat production, considered collectively, results in the export of nitrate to surface waters at a level that is about 9 times greater than estimated from background, 180 kg/km^2-yr in comparison to 21 kg/km^2-yr.

It is important to note that while for comparable land use types the net export coefficients are generally lower for eastern Washington in comparison to western Washington, the impact of the loading for eastern watersheds is more significant due to lower water yields; there is less dilution of the nitrate loading to surface and groundwater. As will be presented, low dilution is also a big factor for the elevated nitrate concentrations observed in several of the eastern Washington drainages that receive municipal wastewater discharge and in the more extensive level of groundwater nitrate contamination observed for eastern Washington in comparison to western Washington. (A discussion of the link between land-surface nitrate loading and its impact on shallow groundwater will be presented later in this report.)

Consider small grain (wheat) production in eastern Washington. Typical fertilization rates are estimated at 8,400 kg/km^2-yr with the net export to surface water at 130 kg/km^2-yr, accounting for plant uptake and attenuation. In total this is a net reduction of 98% between the fertilizer applied and that exported. Despite this substantial reduction, the 130 kg/km^2-yr net DIN export level is still over 6 times greater than the estimated background level.

With the establishment of these export coefficients, the relative effect of these various land uses on surface water nitrate levels, based on their presence and intensity (spatial extent), within a drainage, can be determined. However, the real effect can only be determined by also accounting for several additional nitrate sources.

Additional nitrate sources

Municipal wastewater discharge

Reported DIN (total ammonia and nitrate-nitrite) levels obtained from Washington State Department of Ecology’s water quality Permit and Reporting Information System (PARIS) were used to determine typical municipal wastewater treatment plant (WWTP) effluent levels https://fortress.wa.gov/ecy/wqreports/public/f?p=110:1:36864679157725. (The PARIS database also contains monthly average plant discharge levels for each municipal wastewater treatment plant in Washington.)

Within the database there are 88 wastewater treatment plants that have consistently reported both effluent ammonia and nitrate-nitrite concentrations. From these data, an annual average DIN concentration was determined. Effluent DIN levels among the wastewater treatment plants have relatively high variability from less than 1 mg/L (Hartstene Point STP) to 54 mg/L (Carlyon Beach STP). Both of these facilities have small flows of less than 0.05 million gallons per day (MGD) and can therefore expected to have high variability. For this analysis it is assumed that the typical plant encountered within the study area has no specific process in place to effect enhanced nutrient removal. To offset the higher variability in DIN concentrations observed for facilities with lower flows an overall flow-weighted average concentration was determined. Facilities that had flows that represent greater than 10% to the overall wastewater flow total among those reporting concentrations were removed from the assessment. For instance, the King County West Point WWTP with typical flow of about 200 MGD represented about 45% of the overall flow total and was therefore removed from consideration. The Tacoma Central No. 1 and the Spokane AWWTP facilities were also removed. With the removal of these facilities, a flow-weighted average concentration of 20.6 mg/L was determined. This DIN concentration was then applied to the combined monthly average flows for all WWTPs discharging within each of the study watersheds to determine average monthly and, by summation, annual loads.

An additional assumption applied by this study is that once discharged there is negligible attenuation of DIN associated with WWTP effluent regardless of discharge proximity within the watershed. Without specific targeted data that analyzes effluent attenuation for each discharge, this assumption provides a conservative estimate of effluent effects on downstream DIN concentrations as observed at the monitoring stations. And, as it turns out, this assumption held up well for the majority of the watersheds examined.

Wastewater collection system leakage

Another potential pathway that municipal wastewater can affect stream nitrate concentrations is from collection system leakage to groundwater. This could be a factor with increasing base-flow nitrate levels in drainages situated in more urbanized settings such as the Cedar, Green (Tukwila), and Deschutes Rivers. Typically, for western Washington drainages, nitrate concentrations are positively correlated to flow, with the lowest concentrations occurring at base-flow (refer to Appendix C). However, for each of these more urbanized stations, decreasing flows coincide with increasing nitrate levels suggesting that groundwater with elevated nitrate is discharging to surface water. It is expected that leakage is only a factor for highly urbanized western Washington drainages where sewerage collection systems are of high density. This is because of the age and extent of collection systems and their vertical separation (gradient) to shallow groundwater.

In many agricultural communities in eastern Washington surrounded by irrigated land, there is a net groundwater inflow to wastewater collections systems, eliminating base-flow period leakage. In addition, the majority of municipal wastewater within the greater Puget Sound region is discharged to marine waters whereas in eastern Washington it is discharged to surface waters in proximity to the community collection systems. For this reason, collection system leakage provides a more recognizable signature on stream nitrate concentrations for western Washington in comparison to eastern Washington. The presence and concentration of a tracer such as chloride would be needed to determine whether collection system leakage provides a significant source of nitrate to urban drainages in the greater Puget Sound region.

On-site discharge

Many of the study watersheds have mixed wastewater treatment and disposal methods: municipal-based and residential on-site. Wastewater flows from the municipal discharges were determined from their individual monthly discharge monitoring reports (DMRs) as previously discussed. Based on the reported flows for specific municipal wastewater treatment plants and considering the populations served, an average daily per capita water use of 100-gallons per day (0.38 m^3/d) was determined. This municipally-served population was then subtracted from the greater United States Department of Commerce's Census Bureau-derived watershed population estimates to determine the population within each watershed that utilizes on-site wastewater treatment and disposal.

On-site system effluent, primarily in the dissolved inorganic form of ammonium-N (NH_4+) ion, is estimated at a median concentration of about 58 mg/L (McCray, 2005). A 35% loss in concentration associated with de-nitrification within the drain field (Gurpal, 2011) reduces the concentration to 38 mg/L. The net result is an introduction to groundwater of 14.4 grams DIN per person per day (5.3 kg/capita-yr.). This study will assume a further 60% attenuation for western Washington watersheds and 95% for eastern Washington watersheds consistent with that found for background conditions reflecting further attenuation occurring in the groundwater / surface water flow network.

Dairy, beef, and poultry

A major objective of this study was to provide a relatively simple method to estimate nitrate export based on the representation of various land uses present within a watershed. While this approach works well for land use descriptions such as evergreen forests it does less so for sources such as beef, dairy, and poultry production. This is because forest-lands are well defined within the land use descriptions and provide a more homogeneous effect on nitrate export (i.e. the export of nitrate from evergreen forest-land in the Nisqually watershed is not significantly different than that of the Stillaguamish watershed). In comparison, dairy and poultry operations are not defined in the land use descriptions and are heterogeneous; the proximity of operations throughout the state tend to be clustered and their nitrate export effect, based on the number of animals present per operation, varies significantly. For these reasons, the effect of dairy's nitrate export (in addition to beef and poultry operation influences) was not tied to the land use descriptions. Given the heterogeneity in spatial representation and intensity levels of dairy, beef, and poultry operations within Washington, direct methods were applied to calculate the net nitrate export, again utilizing U.S. Department of Agriculture Census data.

Dairy production

The dairy industry is centered primarily in two counties in Washington: Whatcom and Yakima which account for 26% and 19%, respectively of the state total, by number of operations (Dairy Farmers of Washington, 2014; Figure 5). Dairy operations located on the eastside of the state are managed more intensively in comparison to those in western Washington.

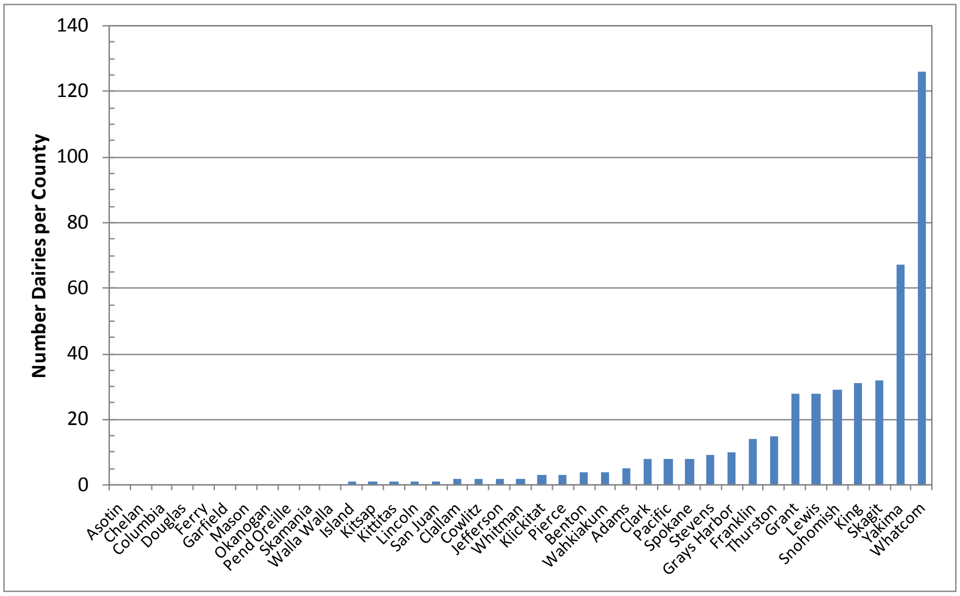

Figure 5. The number of dairies present within each Washington State county.

For instance, while Whatcom County has approximately twice the number of dairies as Yakima County, the average number of milking cows per dairy in Yakima County is about three times greater than that found in Whatcom County, about 1,200 as opposed to about 400 (Figure 6).

Among the data contained within the 2009 USDA agriculture census report for Washington State are estimates of milk cow populations, reported at a county level, for 2007 and 2002 (USDA, 2009). In addition, the proximity of the 445 dairies throughout the state is indicated in a Washington State Department of Ecology geographic information system (GIS) cover (derived from Washington State Department of Agriculture data). Through GIS analysis, the number of dairies situated within each county of the state was determined. It is assumed that each county's milk cow population is solely associated with the dairies situated within it. Following from that assumption, the total number of dairies situated within each watershed was determined, noting also the particular county in which it is situated. A proportion between the numbers of dairies situated within each watershed, by county, in relation to the total number of dairies situated within a particular county was then calculated. This proportion, or factor, was then multiplied by the total population of milk cows reported for the county from the USDA census data. This calculation then provided an estimate of the population of milk cows within each of the study watersheds. Commonly, the study watersheds encompassed multiple counties with dairies situated within many of them. For these cases, the sum of the individual watershed-based county estimates of milk cow populations was taken to estimate the entire watershed population.

The contribution of nitrate associated with dairies was estimated based on the number of dairies present within a watershed, the reported dairy cow population, and typical dairy cow excretion rates and associated N content. The following assumptions were applied:

- A typical annual dairy cow N excretion rate of 169 N kg/cow-yr. (Chang et. al., 2005).
- Total farm-related N losses associated with manure management assuming the use of an anaerobic lagoon for storage with eventual use of the effluent for irrigation/fertilization are 70% of initial loading for western Washington and 50% for eastern Washington. These losses are mainly associated with volatilization and settling. Estimates of lagoon / irrigation system losses range from 78% (Van Horn, 1991) to 40% (University of California, 2005) but are farm specific, temperature and pH-related, among other factors. The eventual loss levels set for eastern and western dairies were determined during calibration at 90% and 50%, respectively.
- An additional net attenuation factor of 0.4 (60% loss) for western Washington dairies and 0.05 (95% loss) for eastern Washington dairies was applied to reflect losses (occurring within the surface/groundwater flow network.

The total net loss in N associated with dairy operations is 96% of gross loading for western Washington and 98% of gross loading for eastern Washington. As will be shown later, even at these high loss levels, dairies, in many instances, have a significant effect on surface and groundwater nitrate levels. In relation to other sources, dairy production is associated with a relatively high transfer rate of surface loading to groundwater. This has to do with the practices characteristic of the modern industry: high waste production volume per animal, high animal densities in confined proximity, and the storage of waste in lagoons which leach to groundwater, among other attributes. In addition to the high volatilization rates as a source of loss, nitrate transferred to groundwater also undergoes loss primarily occurring at the point of its discharge to surface water. As it flows through the riparian zone, where anaerobic conditions and carbon are present, producing an environment for de-nitrification to occur, it is estimated that about 80-90% loss in nitrate occurs at discharge (discussed later). So while dairy production may produce a disproportionate impact to underlying groundwater, from the surface loading perspective, overall loss rates remain high when examined at the surface water outflow from the study watersheds.

Also worth noting, dairy operations typically coincide with the NLCD hay/pasture designation. Dairy waste management in Washington commonly utilizes land application of liquid (manure lagoon) and solids to pasture lands. Due to this intersection, there is the potential to "double count" the nitrate loading effect of dairies. In this analysis it is assumed that hay/pasture production utilizes an N application rate whether that is associated with synthetic fertilizer or animal waste. It can be assumed that for pastures in areas of high dairy production (i.e. Nooksack [Whatcom County] and lower Yakima [Yakima County]) that the primary source is animal waste.

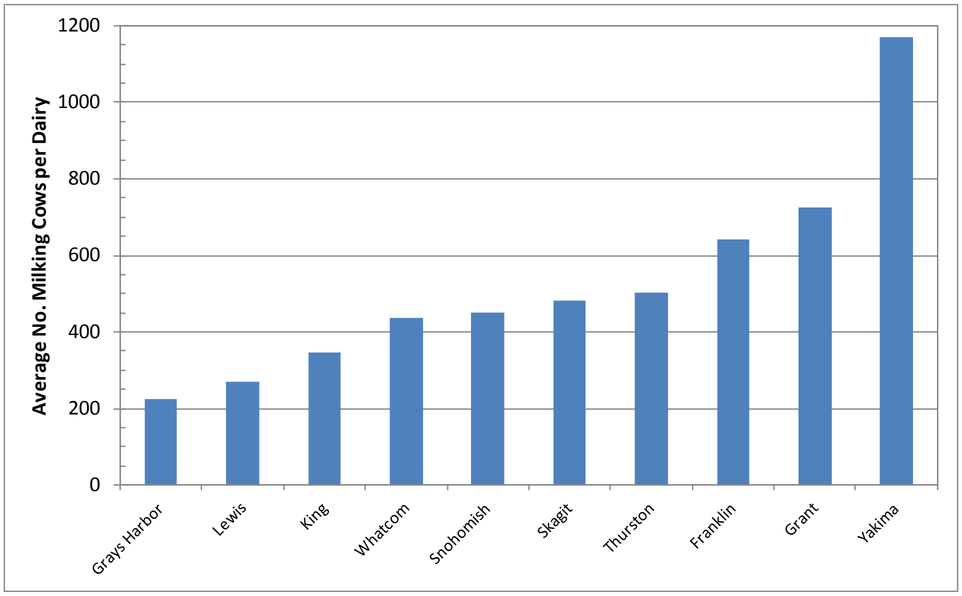

Figure 6. The average number of milking cows per dairy, by county.

Another complicating factor is that dairy waste can be imported or exported from a watershed. While acknowledging that this may occur in some instances, it is assumed that the majority of the dairy waste generated is applied to pastureland within the watershed in which the dairy is located.

Beef cow production

The USDA census data also contains county level estimates of beef cow populations along with an additional designation specified as "other cow". These two populations were grouped and assumed to represent the entire beef cow population. As opposed to dairies, which have a fixed location, beef cows represent a more dispersed population so determining their population within each watershed was approached differently. In this case, the proportion was based on the county area situated within each watershed in relation to the total county area. Similar to the method used to determine the dairy cow population, a proportion was used based on these relationships using area as opposed to dairy operation number. This proportion, or factor, was then multiplied by the total county population of beef and "other" cows to determine a watershed- based population.

Estimates of nitrate export associated with beef cattle production are based on the following assumptions:

- A typical annual beef cow excretion rate of 72 kg N/cow-yr. (Kissinger, 2007).

- Urea accounts for 75% of excreted N with the remainder present within feces (Nader, 1998).
- The volatilization rate of N associated with urine is 80% and 37% for feces (Nader, 1998) resulting in a net percent loss of about 70% of excreted N. The final net volatilization loss used in the estimate is 70%.
- An additional net attenuation factor of 0.4 (60% loss) for west-side watersheds and 0.05 (95% loss) for east-side watersheds.

The combined effect of these assumptions is a net N loss of 88% and 99% of gross loading for western and eastern Washington locations associated with cattle waste.

Poultry production

The USDA Census reports poultry populations based on the primary production end product: eggs (layers) or meat (broilers). Similar to dairy and beef cow populations, the USDA census numbers are reported at a county level. Commercial poultry production is centered in western Washington with egg production primarily occurring in Thurston (64% of state total population), Snohomish (20%), and Skagit (14%) counties and broiler production centered within Cowlitz (12%), Clark (14%), and Lewis (74%) counties. Lewis County is the epicenter of poultry production in the state having a factor of 5 greater numbers of layers and broilers than the next highest county, Clark (Figure 7).

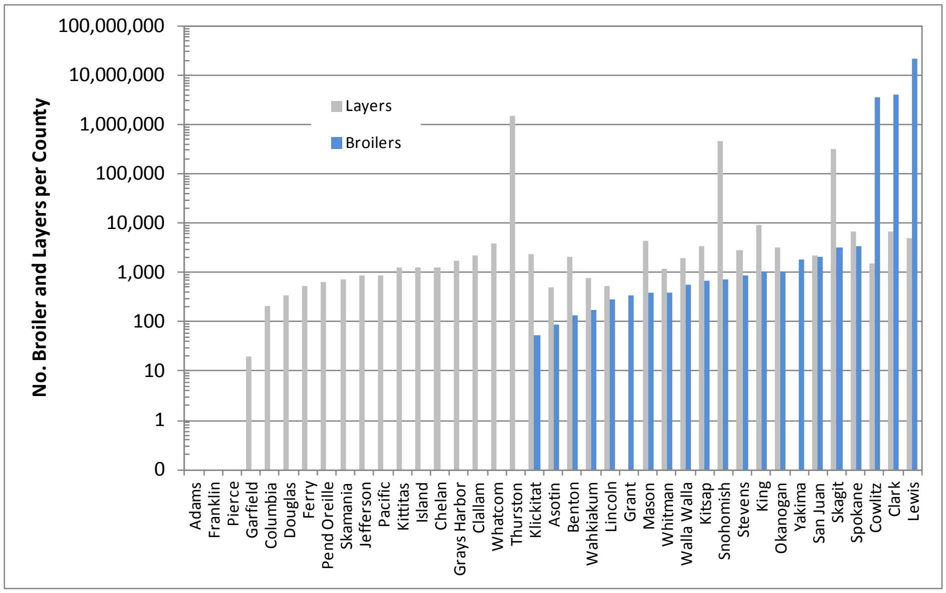

Figure 7. The total number of broilers and layers, by county.

The populations of each poultry-type (layers or broilers) were determined for the study watersheds. The proportional method, used to estimate beef cattle populations, based on county area represented within each of the study watersheds in relation to the total county area, was also used for poultry as a population weighting factor.

Estimates of nitrate export associated with poultry production are based on the following assumptions:

- An annual N excretion rate of 0.42 kg/bird-yr (Schmitt, 1992).
- A volatilization factor of 0.5 reflecting a 35% loss associated with storage (Schmitt, 1992) and 20% loss during land application (Nahm, 2003).
- An additional net attenuation factor of 0.4 (60% loss) for west-side watersheds and 0.05 (95% loss) for east-side watersheds to account for flow network losses. Combined volatilization and environmental (attenuation) losses account for a net level of 80% loss for watersheds situated in western Washington and 97% for eastern Washington.
- The reported county layer populations are assumed to reside on the farm for the entire year. While the broiler population is based on the reported number sold with an average farm residence of 11 weeks (0.21 years) before harvest.
- While differences in manure N content and waste management between layer and broiler production are recognized, it is assumed that these differences are insignificant given the convergence of current overall poultry production practices.

Nitrate sources not considered

Due in part to their low level of representation within the study watersheds, several NLCD land uses were not provided net export coefficients including: quarries/strip mines/gravel pits, wetlands (woody and emergent). It is expected that wetlands provide a sink for nitrate, and their overall effect on the watershed load could be considered similar to that found for the “open water” designation (see next section). Or, if a wetland complex is situated in-line with the main channel flow, then its effect on the watershed nitrate load could be considered by only accounting for the drainage area situated below the wetland as contributing to the overall load.

Routes of loss

Open water - lakes and reservoirs

Several of the monitored watersheds had disproportionately lower nitrate yields than suggested by the type and representation of various land uses present within them. These watersheds included, for eastern Washington: Crab Creek, Wenatchee River and Yakima Rivers, and in western Washington: Cedar, Cowlitz, Elwha, Green, Nisqually, Puyallup, Samish, Skagit and Skokomish Rivers. All have in common a high representation of lakes and (or) reservoirs, typically situated in-line with the main drainage channel (Figure 8).

In fact, for watersheds with a high representation of open water storage, the stream: precipitation nitrate load ratio can be as low as that found for the background watersheds despite, in many cases, a high representation of point and nonpoint nitrate sources. This is due to nitrate’s assimilation in primary production (rooted-plant and algae growth), settling and burial within bottom sediments, and de-nitrification occurring within the water body. Factors affecting the level of nitrate loss within open water include: whether the storage is in-line with the main channel flow, surface area, storage capacity (retention time), its proximity within the watershed (how much of the watershed drains to it), and its level of productivity, among other factors.

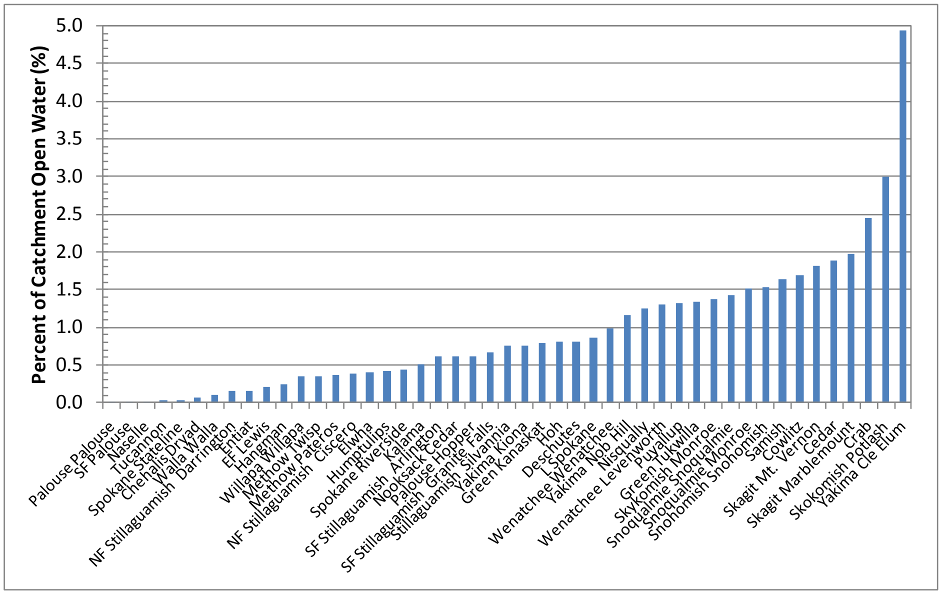

Figure 8. Percent of watershed designated as open water.

To account for this these storage-based loss pathways, two approaches were used with the division based on whether a lake/reservoir was situated in-line with the main channel. In the case of a lake/reservoir receiving main channel flow, an effective drainage area was set based on the portion of the watershed situated below the lake/reservoir. The portion of the watershed situated above the lake/reservoir was assumed to not provide a significant contribution to the nitrate load observed at the downstream monitoring location. While it is recognized that there is nitrate export from the lakes and reservoirs, the level of export is assumed to be insignificant in relation to that associated with sources situated down gradient. This approach has limitations particularly if the point of interest is located in close proximity to the outlet of storage. For these situations, which were rare in this analysis, the outflow nitrate concentration was assumed to be present at the point of detection, 0.01 mg/L.

All loading calculations are based then on the effective drainage area, or the portion of the watershed situated below the lake/reservoir, with nitrate loading solely affected by the land uses present within it. The total estimated annual load for the watershed was multiplied by the ratio of the assumed contributing area (effective area) divided by the total watershed area. The annual yield calculation continues to apply the entire watershed area to this modified load estimate. This is because the total amount of runoff is a function of the entire receiving area.

An important consideration in applying this assumption is the type of storage whether managed, such as the Cle Elum reservoir in the Yakima watershed, or natural, such as Lake Wenatchee in the upper Wenatchee. Managed systems tend to capture and store peak runoff significantly reducing nitrate export, as opposed to natural flow-through systems which tend to have greater export levels particularly during peak flows due to lower residence times.

As will be shown, the application of this approach provided reasonable results to account for this pathway of nitrate loss. It was an essential component of the method to estimate the annual loads for watersheds with reservoir storage. But in application this assumption dismisses nitrate loading occurring up-gradient of the reservoir. So while its application was necessary to accurately predict annual loads observed at monitoring locations, it is limiting in terms of assessing watershed-wide land use and potential impacts to groundwater. The error of this approach increases as the loading assessment point approaches the storage outlet and diminishes the further downstream the point of assessment and increasing effective area.

The recent removal of the Elwha and Glines Canyon dams on the Elwha River would seem an excellent test case to calculate nitrate loss rates occurring in reservoir storage. Unfortunately, recent water quality measurements indicate that reservoir-deposited sediments continue to influence nitrogen levels at the monitoring location. In particular, for much of the year suspended solids concentrations remain elevated indicating continued scouring of previously deposited material and ammonia is detected at levels far exceeding those expected of a relatively un-impacted watershed such as the Elwha. Assuming the same average monthly flows for the Elwha as applied in this study though exchanging the monthly average nitrate levels observed at the Hoh River monitoring station (a nearby watershed with similar drainage area and land cover composition) for those of the pre-dam removal results in a net annual nitrate yield of 130 kg/km^2-yr (this yield is half that assumed for background). The net nitrate yield determined for the Elwha watershed by this study was 25 kg/km^2-yr. Therefore, the overall loss within the previous reservoirs was about 81%. Applying the effective area method, the assumed loss rate is close to that estimated at 90%. The unusually high loss rate for this drainage indicates that sediments will continue to influence downstream dissolved inorganic nitrogen levels for some time.

For many of the other watersheds, nitrate loss occurs through off-channel lakes and wetlands. In these cases, an average settling rate was applied to the total open water surface area present within the watershed, a NLCD designation. The settling loss rates for eastern and western Washington watersheds were set at -1,000 kg /km^2-yr and -5,500 kg/km^2-yr, respectively. These loss rates were determined through final loading calibration. In instances where an effective watershed drainage area was applied, no further application of N loss from open water was applied.

Perennial ice and snow

Perennial ice and snow designated areas were considered long-term storage (glacial or glacial-forming) and therefore another source of DIN loss. The magnitude of the loss was based on the perennial ice and snow designated area (km^2), the average annual precipitation occurring within it, and the assumption of a DIN precipitation concentration of 0.253 mg/L for western situated watersheds and 0.574 mg/L for eastern situated watersheds.

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Application of Loading Methods to Monitored Watersheds

This section presents the relationship between the study watershed's observed net nitrate loads and those estimated through application of the export coefficients and other loading estimate methods. The dominant nitrate sources within each of the study watersheds are presented. These results are then followed by an examination of the link between land surface loading and observed shallow groundwater nitrate concentrations. Then, the loading estimate methods are applied to the Yakima watershed though at a finer spatial resolution than previously applied.

Relationship between estimated and observed loads

Overall, the study method provided reasonable annual nitrate loading estimates when compared to the observed loads for both eastern and western Washington watersheds with an overall median difference of +0.6% (Figure 9). Tables 9 and 10 include the observed and estimated nitrate loads in addition to the percent deviation by monitoring location, for the western and eastern Washington monitoring locations, respectively. For western Washington, the overall median loading difference is +4.3% ranging from an underestimation of 58% for the Naselle River, indicating unaccounted sources, to an overestimation of 34% for the Deschutes.

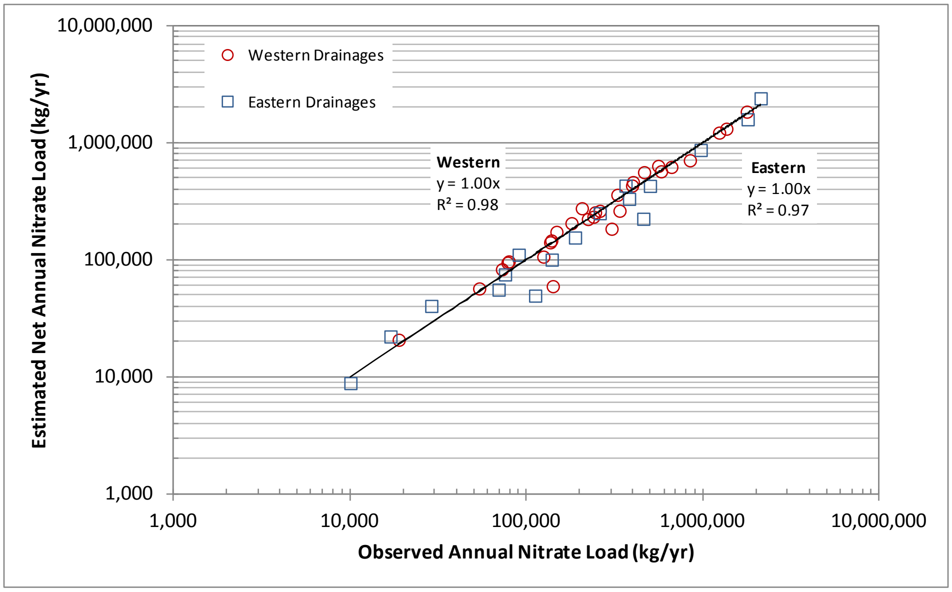

Figure 9. Relationship between observed and estimated annual nitrate loads.

The greatest deviation between observed and estimated loads occurred for several of the low elevation coastal drainages, in particular, the Naselle and Willapa Rivers. The annual loads for both watersheds were underestimated which may be related to the influence of smaller animal operations ("hobby farms") which are not fully accounted for by this study's analysis approach. Animal access to surface waters, and/or animal waste directed to it would be indicted by a low ratio between nitrate and fecal coliform bacteria (i.e. concentrations of nitrate are low relative to those of fecal coliform). Among the western Washington monitoring stations this occurs most prominently for the Naselle, Samish, Green @Tukwila, Snohomish, Stillaguamish @Silvannia, Puyallup, and the Willapa (Figure A-3, Appendix A). With the exception of the Naselle, the percent of the annual nitrate load attributed to animal production (beef, dairy, and poultry) and pasture ranged between 19% (Snohomish) to 36% (Green Tukwila). The Naselle had a level of 4%, a level incongruent in relation to the base flow fecal coliform levels observed. In fact, there was not a hay/pasture designation for the Naselle drainage indicating a limitation of the land cover grid for particular locations. Though the Willapa has about 22% of its annual nitrate load attributed to animal production and pasture management, due to its close proximity to the Naselle, this level could also be underestimated due to NLCD grid extrapolation.

Table 9. Observed and estimated annual nitrate loads, western Washington watersheds.

Station	Effective Area Factor	Annual Nitrate Load (kg/yr)		Annual Average Nitrate Concentration (mg/L)		% Difference
		Estimated	Observed	Estimated	Observed	
Cedar @Logan	===	173,226	147,565	0.319	0.272	17.4
Chehalis @Dryad	===	233,245	239,077	0.475	0.487	-2.4
Cowlitz @Kelso	0.40	1,221,861	1,233,116	0.180	0.181	-0.9
Deschutes @East Bridge	===	275,579	205,548	0.982	0.733	34.1
EF Lewis nr Dollar Corner	===	205,420	179,558	0.416	0.364	14.4
Elwha nr Port Angles	0.10	20,704	18,836	0.019	0.017	9.9
Green @Kanaskat	0.50	96,788	79,113	0.157	0.128	22.3
Green @Tukwila	0.75	461,323	400,362	0.473	0.411	15.2
Hoh @DNR Campground	===	146,090	137,956	0.080	0.076	5.9
Humptulips nr Humptulips	===	106,350	124,346	0.122	0.143	-14.5
Kalama nr Kalama	===	223,046	222,479	0.334	0.333	0.3
Naselle nr Naselle	===	59,476	140,676	0.206	0.488	-57.7
NF Stillaguamish @Ciscero	===	261,980	259,678	0.197	0.195	0.9
NF Stillaguamish nr Darrington	===	82,866	72,486	0.234	0.204	14.3
Nisqually @Nisqually	0.43	431,002	395,943	0.275	0.253	8.9
Nooksack @No. Cedarville	===	560,721	463,132	0.209	0.173	21.1
Puyallup @Meridian St.	0.57	634,080	556,928	0.254	0.223	13.9
Samish nr Burlington	0.86	140,958	135,951	0.766	0.739	3.7
SF Stillaguamish @Arlington	===	254,422	244,250	0.231	0.221	4.2
SF Stillaguamish nr Granite Falls	===	94,444	77,941	0.123	0.101	21.2
Skagit @Marblemount	0.40	359,060	326,880	0.069	0.063	9.8
Skagit nr Mount Vernon	0.53	1,319,086	1,355,138	0.101	0.104	-2.7
Skokomish nr Potlash	0.30	56,841	53,842	0.078	0.074	5.6
Skykomish @Monroe	===	570,384	577,778	0.133	0.134	-1.3
Snohomish @Snohomish	===	1,845,421	1,768,967	0.260	0.249	4.3
Snoqualmie nr Monroe	===	708,579	841,931	0.250	0.297	-15.8
Snoqualmie @Snoqualmie	===	262,514	336,089	0.147	0.188	-21.9
Stillaguamish nr Silvannia	===	621,817	660,957	0.239	0.254	-5.9
Willapa nr Willapa	===	184,172	302,866	0.464	0.763	-39.2

Another possibility for the discrepancy has to do with the level of representation of deciduous trees. The percent of the annual nitrate load associated with deciduous tree cover was 52% for the Willapa River and 45% for the Naselle River. Being able to distinguish nitrate-releasing alders as opposed to other deciduous species such as big-leaf maples (*Acer macrophyllum*), that have no significant effect on in-stream nitrate concentrations, is an important consideration for these lower elevation western Washington drainages. The deciduous export coefficient was set at an average alder representation. Nitrate loading for drainages with high deciduous cover, primarily represented by alder would, therefore, tend to be under estimated. A GIS cover that distinguishes between varying deciduous species, providing a more accurate estimate of alder representation, would likely refine these loading estimates particularly for the low elevation watersheds.

Similarly, the study methods provided good overall estimates of nitrate loading for the eastern Washington drainages. The overall median difference between estimated and observed annual nitrate loads was -11% with a range of +40% (Tucannon River) to -56% (Palouse @Palouse) indicating unaccounted sources, potentially attributed to municipal wastewater discharge occurring in Idaho.

Setting an effective area to watersheds with storage was the only adjustment required for the western Washington drainages. The eastern Washington drainages, due to their increased complexity, required additional considerations. These included accounting for: groundwater inflow (Spokane and Little Spokane River), a higher forest nitrate export level for portions of the eastern Cascades (Wenatchee River), and lower wheat nitrate fertilization levels for the Walla Walla in relation to the other wheat growing areas.

Table 10. Observed and estimated annual nitrate loads, eastern Washington watersheds.

Station	Effective Area Factor	Annual Nitrate Load (kg/yr)		Annual Average Nitrate Concentration (mg/L)		% Difference
		Observed	Estimated	Observed	Estimated	
Crab nr Beverley	0.23	380,701	331,767	1.869	1.629	-12.9
Entiat nr Entiat	===	16,914	22,095	0.045	0.059	30.6
Hangman @mouth	===	458,307	224,136	3.798	1.857	-51.1
L Spokane nr mouth	===	500,105	428,159	1.066	0.913	-14.4
Methow nr Pateros	===	90,161	110,404	0.080	0.098	22.5
Methow @Twisp	===	75,432	74,943	0.069	0.069	-0.6
Palouse @Hopper	===	969,353	868,264	2.814	2.521	-10.4
Palouse @Palouse	===	111,755	49,363	0.525	0.232	-55.8
SF Palouse @Pullman	===	138,753	100,285	5.700	4.120	-27.7
Spokane @Riverside	0.29	2,120,293	2,382,745	0.432	0.485	12.4
Tucannon @Powers	===	28,814	40,300	0.243	0.341	39.9
Walla Walla nr Touchet	===	259,568	250,183	0.681	0.657	-3.6
Wenatchee nr Leavenworth	0.58	69,363	55,550	0.041	0.033	-19.9
Wenatchee @Wenatchee	0.79	188,054	154,948	0.080	0.066	-17.6
Yakima nr Cle Elum	0.23	10,026	8,827	0.019	0.017	-12.0
Yakima @Kiona	0.95	1,789,967	1,589,133	0.826	0.734	-11.2
Yakima @Nob Hill	0.90	363,516	430,402	0.128	0.152	18.4

This study assumes that for the majority of the watersheds examined, that groundwater inflow provides a steady but relatively minor source of nitrate loading when examined on an annual basis. This proved to be the case with the Little Spokane and Spokane River, the exception. Due to the significance of groundwater discharge and the Spokane Valley – Rathdrum Prairie Aquifers' elevated nitrate concentrations it became apparent, through the methods employed, that a major source was missing for both of these drainages.

Groundwater discharge to the Spokane River (in proximity to the Riverside monitoring station) has been estimated at approximately 17 cubic meters per second (m^3/s) (Kahle, 2007). A similar level is found by examining the observed flows at the Spokane River at the Riverside monitoring station in relation to the other inflow sources for the month of September. September provides the best assessment period of the base flow condition for the Spokane River. Subtracting the monthly median flows observed at the Spokane River at the Idaho/Washington border (Stateline monitoring location), the city of Spokane WWTP and the Hangman Creek tributary from the flow observed at the Riverside monitoring location results in a groundwater inflow estimate of 16 m^3/s. The annual average groundwater inflow to the Little Spokane River, also derived from the Spokane Valley – Rathdrum Prairie Aquifer, is estimated at 6.6 m^3/s (Kahle, 2007). Because both drainages share a common source of groundwater, it is assumed that the median groundwater nitrate concentration is the same. Groundwater nitrate concentrations collected by various agencies (United State Geologic Survey, Washington State Department of Ecology, and the Washington State Department of Health) within the greater Spokane Aquifer for well depths less than 30-meters were found to have a median concentration of 1.4 mg/L. Based on this concentration and the groundwater inflow levels, the annual nitrate load to the Little Spokane River and the Spokane River attributed to groundwater inflow is approximately 321,000 and 787,000 kilograms, respectively.

The forest-land nitrate export coefficient for the eastern Washington forest-lands was set at 21 kg/km^2-yr. This proved too low for the forest-lands of the upper Wenatchee and Yakima watersheds. The tree species represented and the precipitation conditions in the upper portions of both of these drainages have more in common with those of western Washington than the shrub-lands more representative of greater eastern Washington. An underlying factor in determining the net export coefficients is the level of precipitation within the watershed. For simplicity, just an eastern and western Washington background (forest-lands, shrub-lands) export coefficient was determined and applied. For the majority of the watersheds, this division provided reasonable annual loading estimates. It is within the transitional areas, particularly the south eastern slopes of the Cascades, where background loading is underestimated. The export coefficient applied to the Yakima at Cle Elum and the Wenatchee stations was set at 42 kg/km^2-yr, 84% lower than applied to western Washington forest-lands, but a factor of two greater than applied to the rest of the eastern Washington forest-lands (which included the scrub-lands). This adjusted export coefficient was not applied to the lower Yakima since the upper portion of its watershed represents a relatively insignificant source of its annual load total (due in part to reservoir storage) in comparison to those located in the lower valley. In the Wenatchee, the upper elevation forest-lands do represent a significant portion of the watershed and the reason why the increased forest-land export coefficient was applied for the entire watershed.

The small grain (wheat) nitrate fertilization level of 130 kg/km^2-yr provided a reasonable fit for most of the drainages with high representations of wheat production with the exception of the Walla Walla and its tributary, the Tucannon River. For both of these drainages, a significantly lower level of 26 kg/km^2-yr provided a better estimate than the 130 kg/km^2-yr export level applied to the greater Palouse region. This level is essentially the same as background. Fertilization rates are dependent, in part, on precipitation levels but the Palouse and Walla Walla share similar annual levels. It may be that the actual level of fertilization associated with wheat production has high variability with local farming practices posing an additional factor.

It is recognized that based on the generalized approach taken to estimate the annual nitrate loads that there cannot be a complete agreement between those estimated and observed. The data used and methods applied does not fully account for the unique characteristics of each watershed. However, the main frame of reference is not necessarily on a watershed-to-watershed basis, though this is obviously important. Rather, it is on whether, as a whole, do the net export coefficients applied, and the overall method capture, the variation in loading as a consequence of changing land use practices and activities? From this perspective, the coefficients and analysis methods provide a good fit for the majority of the monitoring locations.

Representation of nitrate sources

Western Washington watersheds

The percent of the annual load attributed to the various nitrate sources examined for each of the western Washington watersheds is presented in Table 11. Overall, due to its high level of representation, forest-lands are the greatest source of nitrate within the study watersheds, contributing an average of 51% of the annual load, with a range from 20% (Samish) to 84% (Elwha).

Forest is assumed to represent a background nitrate loading condition indicating that the majority of the study watersheds are largely buffered from the higher level loading associated with some of the other land use types and activities. Forest cover tends to have greater representation in the upper portions of each watershed (coinciding with where the greatest precipitation levels occur) with the majority of the other land uses and activities that generate greater loading situated in the lower valleys. From a watershed perspective, the storage of snow along with the high representation of forests at the upper elevations, buffers lower valley water quality impacts. Greater loading impacts would, therefore, occur for watersheds with lower relief (minimal snow storage) and a lower representation of forest cover, a condition most representative of the low elevation-type watersheds such as Samish, Willapa, and the Deschutes.

Figure 10 presents the estimated annual nitrate yields (kg/km^2-yr) for the study watersheds in ascending order. With the exception of the Hoh River, watersheds with the nine lowest yields all have reservoir storage. Among this group, the median annual nitrate yield is 190 kg/km^2-yr, lower than that assumed for a background loading condition (forest cover was considered to represent background at 266 kg/km^2-yr). The Snoqualmie @Snoqualmie annual yield is just outside those affected by storage with annual yields at 277 kg/km^2-yr. In comparison, the median among study watersheds with the nine highest yields is 490 kg/km^2-yr, about an 84% increase in yield beyond background. Six of the nine highest yields are all observed for low elevation type watersheds.

While using the percent of the annual load ascribed to each of the nitrate sources works well to determine the dominant sources on a watershed by watershed basis, it does not provide a relevant metric for comparisons among the watersheds due to the varying magnitudes of their annual loads and unique physical characteristics. Therefore, the influence of individual station loading, by land use or activity type, was also expressed in terms of yields. This perspective provides a means to compare, among the stations, the relative influence of each nitrate source.

For instance, in the case of the Humptulips River, the annual yield, considering all sources, is about 300 kg/km^2-yr. Referring to Table 13, the primary nitrate sources within the watershed are forest and deciduous cover which comprise 74% and 20% or the annual load, respectively. When these percent’s (expressed as a decimal) are multiplied by the overall annual yield, the resulting forest and deciduous yields are 229 kg/km^2-yr and 61 kg/km^2-yr, respectively. In comparison, the Samish River is estimated to have 20% and 45% of its annual nitrate load from forest and deciduous cover, respectively. It has an annual overall nitrate loading yield of 632 kg/km^2-yr resulting in the forest and deciduous covers having yields of 127 and 285 kg/km^2-yr, respectively. The relative contribution of forest cover among the sources contributing to the overall annual load for the Samish River is about 45% lower in comparison to the Humptulips River. The annual contribution of nitrate associated with the deciduous cover for the Samish is the highest of the study watersheds, and is a factor of five greater than that estimated for the Humptulips (Figure 10).

Table 11. Percent of the net annual load attributed to various sources, western Washington watersheds.

Station	Urban	Bare Rock	Forest-land	Deciduous Tree	WWTP Discharge	On-site	Dairy	Beef	Poultry	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Cedar @Logan	14.2	0.1	58.8	18.7	===	===	===	4.9	===	2.2	0.9	===	===	===
Chehalis @Dryad	0.5	===	44.0	31.4	2.5	===	===	5.4	8.7	6.5	===	0.1	0.1	0.8
Cowlitz @Kelso	0.9	1.0	41.1	20.5	8.6	===	0.8	4.2	8.4	12.1	0.6	0.1	0.2	1.6
Deschutes @E. Bridge	5.6	===	25.9	21.6	===	10.2	2.3	6.9	8.4	16.7	0.7	1.2	===	0.4
EF Lewis nr Dollar Corner	1.3	===	39.0	26.5	===	10.3	===	8.2	5.6	6.6	2.0	===	0.1	0.2
Elwha nr Port Angles	===	3.4	84.3	7.5	===	0.7	===	1.7	===	0.1	2.2	===	===	===
Green @Kanaskat	0.3	0.2	77.1	13.4	===	1.6	===	5.8	===	===	1.5	===	===	===
Green @Tukwila	16.5	0.1	36.6	15.6	===	===	4.2	3.6	===	21.4	1.0	0.3	0.4	0.4
Hoh @DNR Campground	===	7.2	73.5	16.2	===	0.1	===	1.0	===	0.4	1.4	===	===	===
Humptulips nr Humptulips	===	===	74.0	19.9	===	1.2	===	3.3	===	1.5	0.2	===	===	===
Kalama nr Kalama	0.3	0.4	46.6	41.9	===	3.6	===	2.4	4.6	0.2	0.1	===	===	===
Naselle nr Naselle	===	===	51.0	44.0	===	0.9	===	4.0	===	===	===	===	===	===
NF Stillaguamish @Ciscero	0.3	0.9	53.8	21.7	===	2.7	1.1	8.4	1.5	8.2	1.1	0.2	===	0.1
NF Stillaguamish nr Darrington	0.3	1.2	56.6	23.9	===	2.9	===	8.8	1.6	3.1	1.7	===	===	===
Nisqually @Nisqually	2.1	0.3	36.4	21.1	1.2	14.2	===	4.6	4.4	12.0	1.1	1.8	===	0.8
Nooksack @No. Cedarville	0.3	2.0	48.2	21.8	===	2.7	1.4	14.7	0.1	6.2	1.5	0.4	0.1	0.7
Puyallup @Meridian St.	5.8	1.3	45.2	11.4	12.8	===	4.3	3.7	===	12.0	1.1	0.8	0.1	1.4
Samish nr Burlington	2.0	===	20.0	45.1	===	8.2	2.0	6.3	0.5	14.5	0.2	0.4	0.1	0.7
SF Stillaguamish @Arlington	1.5	0.7	54.4	17.2	===	10.0	2.2	7.9	1.7	2.8	1.3	===	0.1	0.2
SF Stillaguamish nr Granite Falls	0.3	1.9	70.2	10.2	===	3.1	===	9.8	2.1	===	2.5	===	===	===
Skagit @Marblemount	0.2	7.4	60.6	7.1	===	0.3	===	16.9	0.7	0.2	6.7	===	===	===
Skagit nr Mount Vernon	0.6	5.2	52.1	14.8	2.9	1.2	1.1	11.8	1.0	4.7	3.9	0.1	0.2	0.4
Skokomish nr Potlash	0.4	0.6	72.9	17.6	===	1.5	===	1.7	===	4.0	1.3	===	===	===
Skykomish @Monroe	0.7	2.8	62.1	13.2	1.5	3.7	0.9	7.7	1.3	2.6	3.3	0.1	0.1	0.1
Snohomish @Snohomish	2.8	1.2	42.6	15.0	7.1	12.1	1.6	5.1	0.7	8.7	1.9	0.1	0.3	0.7
Snoqualmie nr Monroe	2.2	1.0	45.5	14.0	7.0	11.5	1.7	4.0	0.1	9.5	2.0	0.2	0.3	0.9
Snoqualmie @Snoqualmie	2.1	2.9	63.7	10.4	4.3	5.5	===	5.3	===	1.2	4.5	===	===	===
Stillaguamish nr Silvannia	1.1	0.6	47.1	20.5	4.8	4.2	1.8	7.3	1.4	9.5	1.0	0.1	0.1	0.3
Willapa nr Willapa	0.3	===	31.8	48.7	===	0.9	0.8	2.9	===	14.5	===	===	===	===

Since forest cover is the background reference condition, its level of representation within a watershed is important in buffering impacts associated with other land uses and activities that generate higher nitrate export levels. Considering the yields associated with the deciduous cover, the watersheds with greater relief tend to have the lowest levels in comparison to those situated at the lowest elevations like the Chehalis @Dryad. Because of its relatively high level of nitrate export, about four times greater than forest (1,000 kg/km^2-yr as opposed to 266 kg/km^2-yr), as a source, deciduous cover can contribute up to 50% of the annual load for the low elevation watersheds such as the Kalama, Naselle, Samish, Willapa (Table 12).

Alternatively, these data can be examined with the exclusion of background sources, putting the focus on anthropogenic-derived sources (Figure 11, Table 12). Background sources are defined here to include the bare-rock, forest (the combined evergreen, transitional, mixed forest, shrub land), and deciduous land cover designations. The deciduous cover is included as background, though it is recognized that its level of representation may be the result of anthropomorphic-generated disturbance. It is assumed that these land covers represent a background-type condition and their removal from the analysis then puts the focus on the other nitrate sources which have a more direct link to anthropomorphic activities. These are the controllable sources. Watersheds with the highest representation of non-background type source loading would potentially represent the most impacted, depending on the nitrate source and its representation.

From this perspective, background sources contribute about 75% of the annual nitrate load among the study drainages with a range of between 97% (Hoh) to 48% (Deschutes) (Table 12). Among the monitoring stations, the upper and lower quartile for the percent of the annual load attributed to background sources is 65% and 82%, respectively. Monitoring stations with greater than 82% of the annual load attributed to background sources include: Kalama, Green (Kanaskat), Skokomish, SF Stillaguamish, NF Stillaguamish, Humptulips, Naselle, Elwha, and Hoh. Those with less than 60% background include: Snoqualmie (Monroe), Nisqually, Snohomish, Puyallup, Green (Tukwila), and the Deschutes. The Deschutes and Green @Tukwila drainages have the lowest representation of background nitrate sources, though still collectively represents about 50% of the annual total.

Figure 11 presents the nitrate yield associated with the other nitrate sources considered, though having excluded those considered background. (Note: graphics have varying scales.) From this perspective, the relative effect of each major source among the stations can be examined in addition to the loading of each station individually. For instance, consider the Deschutes River. With the background sources removed, the Deschutes River has the highest estimated nitrate yield among the study watersheds at about 347 kg/km^2-yr. Loading is associated with a variety of sources including: pasture (32%), dairy (4%), urban (11%), beef cattle (13%), on-site (19%), and poultry (16%).

Together, these data allow the identification of watersheds receiving higher levels of nitrate loading (relative to others), while also indicating the dominant sources specific to each watershed.

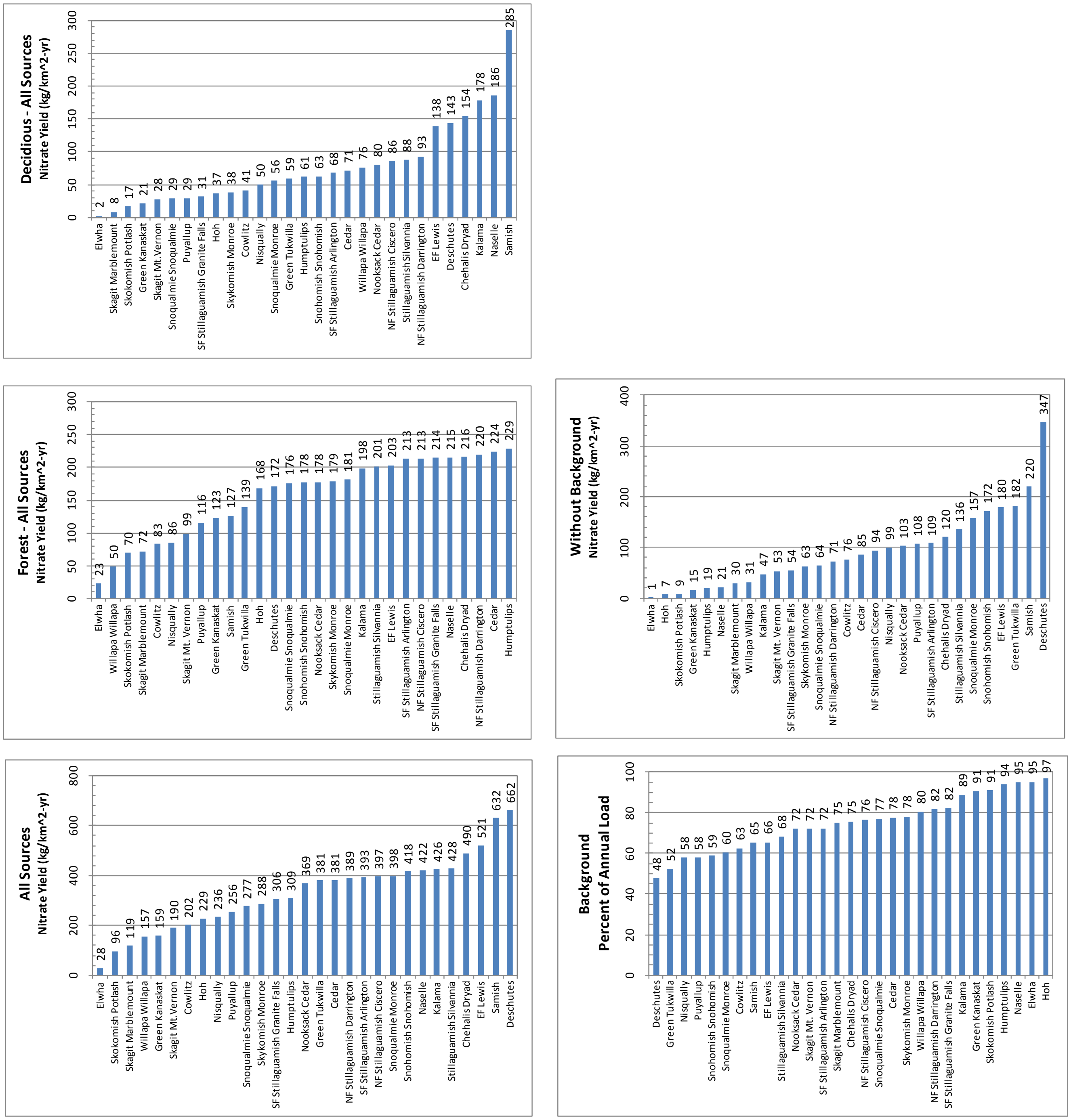

Figure 10. Estimated nitrate yields considering all sources, forest, and deciduous exclusively, western Washington watersheds.

Table 12. Percent of annual load attributed to various sources, excluding background, western Washington watersheds.

Station	% Background	% non – Background	Percent of non-background nitrate load attributed to various sources										
			Urban	WWTP Discharge	On-site	Dairy	Beef	Poultry	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Cedar @Logan	77.6	22.4	63.6	===	===	===	21.8	0.2	9.9	4.2	===	0.2	===
Chehalis @Dryad	75.4	24.6	1.8	10.3	===	===	21.9	35.4	26.5	0.1	0.3	0.4	3.3
Cowlitz @Kelso	62.5	37.5	2.3	22.8	===	2.1	11.3	22.4	32.2	1.7	0.3	0.6	4.3
Deschutes @East Bridge	47.5	52.5	10.7	===	19.4	4.4	13.1	16.0	31.9	1.4	2.3	===	0.7
EF Lewis nr Dollar Corner	65.5	34.5	3.8	===	30.0	===	23.8	16.2	19.2	5.8	0.1	0.4	0.7
Elwha nr Port Angles	95.2	4.8	0.6	===	15.5	===	36.0	0.2	2.7	44.9	===	0.1	===
Green @Kanaskat	90.7	9.3	3.3	===	17.0	===	62.9	0.4	0.2	16.1	===	===	===
Green @Tukwila	52.3	47.7	34.6	===	===	8.8	7.5	0.1	44.7	2.1	0.7	0.9	0.7
Hoh @DNR Campground	96.9	3.1	0.2	===	4.5	===	34.0	0.1	14.0	46.7	0.2	===	0.2
Humptulips nr Humptulips	93.8	6.2	0.3	===	19.1	===	53.8	0.1	23.5	2.7	===	===	0.5
Kalama nr Kalama	88.9	11.1	2.3	===	32.1	===	21.3	41.4	2.0	0.5	0.1	0.1	0.2
Naselle nr Naselle	95.1	4.9	0.4	===	17.9	===	81.3	0.1	===	0.2	===	===	===
NF Stillaguamish @Ciscero	76.4	23.6	1.3	===	11.5	4.7	35.5	6.3	34.6	4.6	0.8	0.2	0.4
NF Stillaguamish nr Darrington	81.7	18.3	1.5	===	15.8	===	48.1	8.5	16.8	9.1	===	0.1	===
Nisqually @Nisqually	57.9	42.1	4.9	2.8	33.7	===	10.8	10.5	28.5	2.6	4.3	===	1.8
Nooksack @No. Cedarville	72.0	28.0	1.1	===	9.6	5.0	52.4	0.5	22.2	5.3	1.4	0.2	2.3
Puyallup@Meridian St.	57.9	42.1	13.8	30.4	===	10.2	8.8	===	28.6	2.7	1.9	0.2	3.3
Samish nr Burlington	65.1	34.9	5.7	===	23.6	5.7	18.0	1.5	41.6	0.7	1.0	0.3	1.9
SF Stillaguamish @Arlington	72.3	27.7	5.4	===	36.2	8.0	28.4	6.0	9.9	4.6	0.2	0.3	0.8
SF Stillaguamish nr Granite Falls	82.2	17.8	1.7	===	17.6	===	55.1	11.7	===	13.9	===	===	===
Skagit @Marblemount	75.0	25.0	0.8	0.1	1.1	===	67.7	2.8	0.7	26.7	===	===	===
Skagit nr Mount Vernon	72.1	27.9	2.3	10.5	4.2	4.0	42.1	3.7	16.7	14.1	0.4	0.6	1.4
Skokomish nr Potlash	91.1	8.9	4.1	===	16.4	===	19.3	0.5	44.6	14.4	0.5	===	0.3
Skykomish @Monroe	78.1	21.9	3.4	6.8	16.9	3.9	35.1	5.7	11.9	15.2	0.3	0.3	0.6
Snohomish @Snohomish	58.7	41.3	6.9	17.3	29.3	4.0	12.4	1.6	21.1	4.7	0.4	0.7	1.8
Snoqualmie nr Monroe	60.5	39.5	5.6	17.8	29.2	4.4	10.2	0.2	24.1	5.0	0.5	0.8	2.2
Snoqualmie @Snoqualmie	77.0	23.0	9.1	18.8	23.9	===	23.2	0.2	5.1	19.5	0.1	0.1	0.1
Stillaguamish nr Silvannia	68.3	31.7	3.5	15.1	13.2	5.7	23.1	4.5	29.8	3.2	0.4	0.4	1.0
Willapa nr Willapa	80.5	19.5	1.4	===	4.9	4.3	14.9	===	74.4	0.2	===	===	===

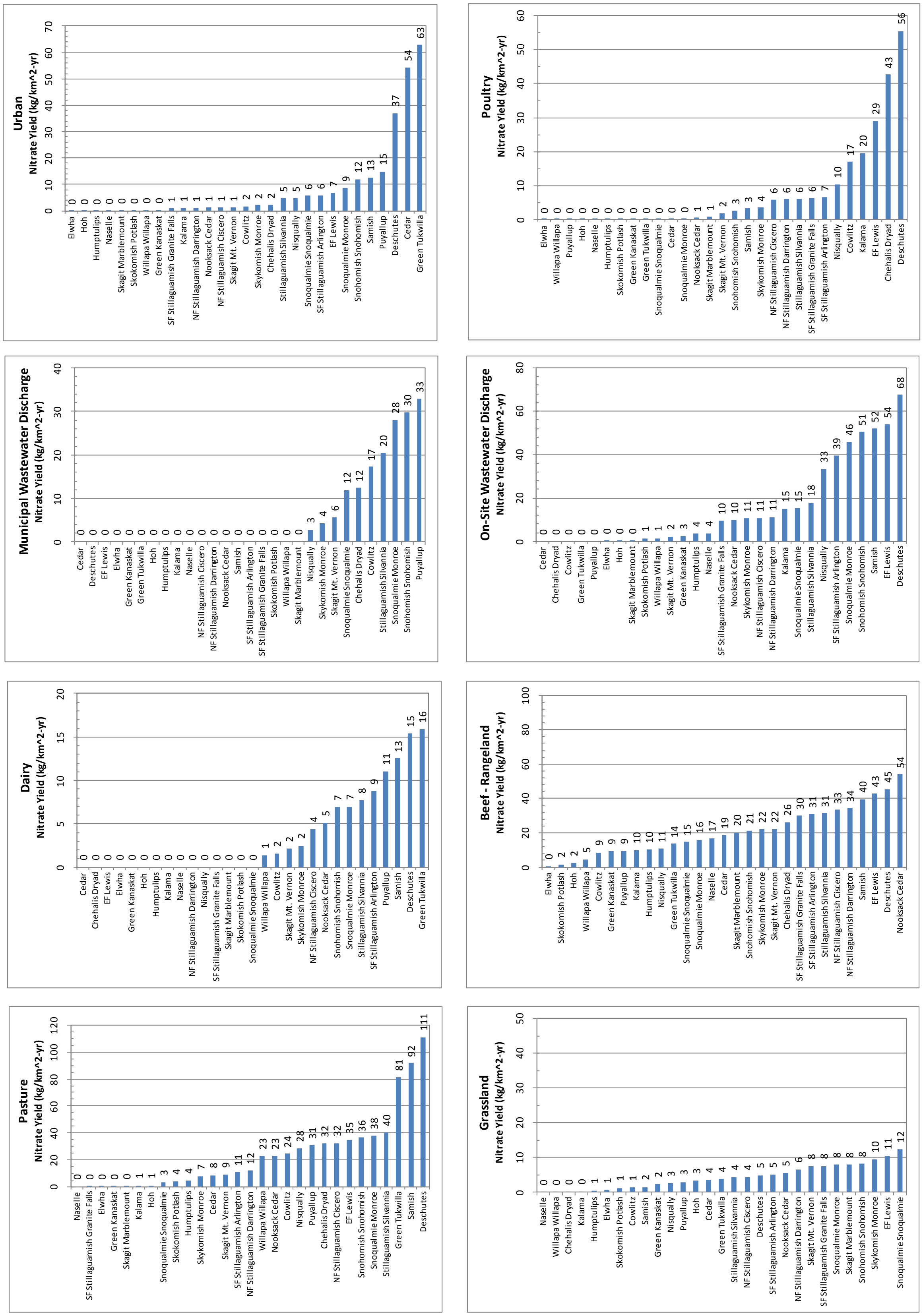

Figure 11. Net nitrate annual yields, by land use type (or activity), excluding background sources, western Washington watersheds.

Eastern Washington watersheds

Background sources of nitrate represent a much lower portion of the overall annual load for eastern Washington watersheds in comparison to those on the state's west-side (Table 13). Even with the removal of the background associated load, the annual nitrate yield is not significantly affected for the majority of the watersheds (Table 14, Figure 12). The exception are watersheds draining the eastern slopes of the Cascades where background nitrate sources represented about 63% (Methow and Entiat Rivers) to 74% (Wenatchee, Yakima @Cle Elum) of the annual load. For the other watersheds, the median level was 7.4% with a range of between 0.7% (South Fork Palouse) to 30% (Yakima @Nob Hill).

Table 13. The percent of the annual load attributed to various sources, eastern Washington watersheds.

Station	Urban	Bare Rock	Shrub / Forest	Deciduous Tree	WWTP Discharge	On-site	Dairy	Beef	Poultry	Pasture	Grass-land	Orchard	Small Grain	Row Crop	Groundwater*
Crab nr Beverley	0.5	===	7.4	===	14.0	0.4	6.9	11.2	===	5.8	1.2	0.6	48.2	3.9	===
Entiat nr Entiat	0.2	4.0	68.9	0.5	===	1.8	===	1.0	===	===	19.1	4.5	===	===	===
Hangman @mouth	0.7	===	4.5	===	24.5	4.2	===	2.5	===	===	0.9	===	62.5	===	===
L Spokane nr mouth	0.5	===	5.4	===	2.4	6.3	1.1	1.6	===	4.1	0.5	===	4.9	0.6	72.5
Methow nr Pateros	0.3	2.2	58.1	0.3	3.3	1.1	===	12.6	===	0.7	16.8	4.0	0.4	0.1	===
Methow @Twisp	0.2	3.1	61.7	0.4	2.0	1.0	===	12.9	===	1.0	14.5	2.9	0.1	0.2	===
Palouse @Hopper	0.4	===	6.5	===	13.0	0.4	0.1	2.2	===	===	0.6	===	76.8	===	===
Palouse @Palouse	0.5	0.1	25.2	===	6.5	===	===	===	===	0.1	0.1	===	67.5	===	===
SF Palouse @Pullman	0.6	===	0.7	===	62.6	===	===	0.2	===	===	===	===	36.0	===	===
Spokane @Riverside	1.0	===	1.5	===	55.5	===	===	===	===	1.3	0.8	1.0	6.7	===	32.1
Tucannon @Powers	0.5	0.1	32.8	0.2	9.9	0.2	===	11.9	===	6.0	12.7	===	25.8	===	===
Walla Walla nr Touchet	0.8	===	12.2	0.3	36.6	===	===	7.9	===	4.6	2.8	3.4	21.8	9.6	===
Wenatchee nr Leavenworth	0.1	7.8	83.7	1.1	1.7	===	===	0.6	===	0.2	4.4	0.4	===	===	===
Wenatchee @Wenatchee	0.2	4.4	66.2	0.9	13.0	2.0	===	0.5	===	0.2	5.9	6.7	0.1	===	===
Yakima nr Cle Elum	0.4	1.3	74.3	0.4	9.5	0.2	===	10.5	===	1.3	2.0	0.1	===	===	===
Yakima @Kiona	0.5	0.2	13.0	0.1	34.6	1.3	20.3	9.5	===	4.1	3.1	5.4	8.0	===	===
Yakima @Nob Hill	0.6	0.5	29.1	0.2	33.1	2.0	0.4	15.2	===	5.0	4.0	5.0	4.9	===	===

*Groundwater load only considered for the Spokane and Little Spokane Rivers

The two highest nitrate yields for the eastern drainages were found for the South Fork Palouse (302 kg/km^2-yr) and the Spokane River @Riverside (644 kg/km^2-yr) and are largely the result of municipal wastewater discharge (Figure 13). Nitrate loading associated with municipal wastewater comprises 63% and 56% of the annual load for the South Fork Palouse and the Spokane River, respectively. Nitrate associated with discharge from the Rathdrum – Spokane

Valley Aquifer comprised an additional 32% of the annual load observed for the Spokane River @Riverside. For the South Fork Palouse, the other major nitrate source is associated with wheat production (small grain), representing 36% of the annual total. The nitrate yield specifically associated with wheat production was estimated at 109 kg/km^2-yr, the highest among the study watersheds (Figure 13). Due to the high representation of wheat production for the greater Palouse, it comprises the single greatest source of nitrate for the area followed by municipal wastewater discharge. The annual nitrate load observed for the Palouse @Hopper is estimated to be 77% derived from wheat production. Wheat production also contributed to nitrate export for watersheds beyond the Palouse such as Crab Creek where it comprises 48% of the annual load.

Table 14. The percent of the annual load attributed to various sources, excluding background, eastern watersheds.

Station	% Background	% non – Background	Percent of non-background nitrate load attributed to various sources											
			Urban	WWTP Discharge	On-site	Dairy	Beef	Poultry	Pasture	Grass-land	Orchard	Small Grain	Row Crop	Groundwater
Crab nr Beverley	7.4	92.6	0.5	15.2	0.4	7.4	12.1	===	6.2	1.3	0.6	52.1	4.2	===
Entiat nr Entiat	73.3	26.7	0.6	===	6.8	===	3.9	===	0.1	71.7	16.8	===	===	===
Hangman @mouth	4.6	95.4	0.7	25.7	4.4	===	2.6	===	===	1.0	===	65.5	===	===
L Spokane nr mouth	5.5	94.5	0.6	2.5	6.7	1.2	1.7	===	4.3	0.5	===	5.2	0.6	76.7
Methow nr Pateros	60.7	39.3	0.6	8.3	2.8	===	32.0	===	1.8	42.8	10.1	1.1	0.3	===
Methow @Twisp	65.1	34.9	0.7	5.7	3.0	===	37.1	===	2.8	41.5	8.4	0.3	0.5	===
Palouse @Hopper	6.5	93.5	0.4	13.9	0.4	0.1	2.3	===	===	0.7	===	82.1	===	===
Palouse @Palouse	25.3	74.7	0.7	8.8	===	===	===	===	0.1	0.2	===	90.3	===	===
SF Palouse @Pullman	0.7	99.3	0.6	63.0	===	===	0.2	===	===	===	===	36.2	===	===
Spokane @Riverside	1.5	98.5	1.1	56.3	===	===	===	===	1.4	0.8	1.0	6.9	===	32.6
Tucannon @Powers	33.1	66.9	0.7	14.8	0.3	===	17.8	===	8.9	19.0	===	38.5	===	===
Walla Walla nr Touchet	12.4	87.6	0.9	41.8	===	===	9.0	===	5.2	3.2	3.9	24.9	11.0	===
Wenatchee nr Leavenworth	92.6	7.4	0.9	23.3	===	===	8.0	===	2.7	59.0	6.0	===	===	===
Wenatchee @Wenatchee	71.4	28.6	0.8	45.4	7.1	===	1.7	===	0.6	20.5	23.4	0.3	0.1	===
Yakima nr Cle Elum	76.0	24.0	1.5	39.4	0.9	===	43.9	===	5.5	8.5	0.3	===	===	===
Yakima @Kiona	13.2	86.8	0.5	39.9	1.5	23.4	11.0	===	4.7	3.5	6.2	9.2	===	===
Yakima @Nob Hill	29.8	70.2	0.9	47.1	2.8	0.5	21.6	===	7.1	5.7	7.1	7.0	===	===

Nitrate associated with groundwater discharge to the Little Spokane River from the Rathdrum – Spokane Valley Aquifer accounts for about 77% of the annual load for the drainage. The other major source, also groundwater-based, is on-site wastewater discharge, accounting for 7% of the annual load total.

The representation of nitrate sources observed at the Yakima River @Kiona monitoring station were broad-based with municipal wastewater discharge and dairy operations having the greatest representation at 35% and 20% of the annual load (Table 13). On the west side of the state the majority of the wastewater is discharged to marine waters, while on the east side discharge tends to be directed to the nearest surface water though there is a greater movement now toward land application (highly represented in the Crab Creek and Walla Walla watersheds).

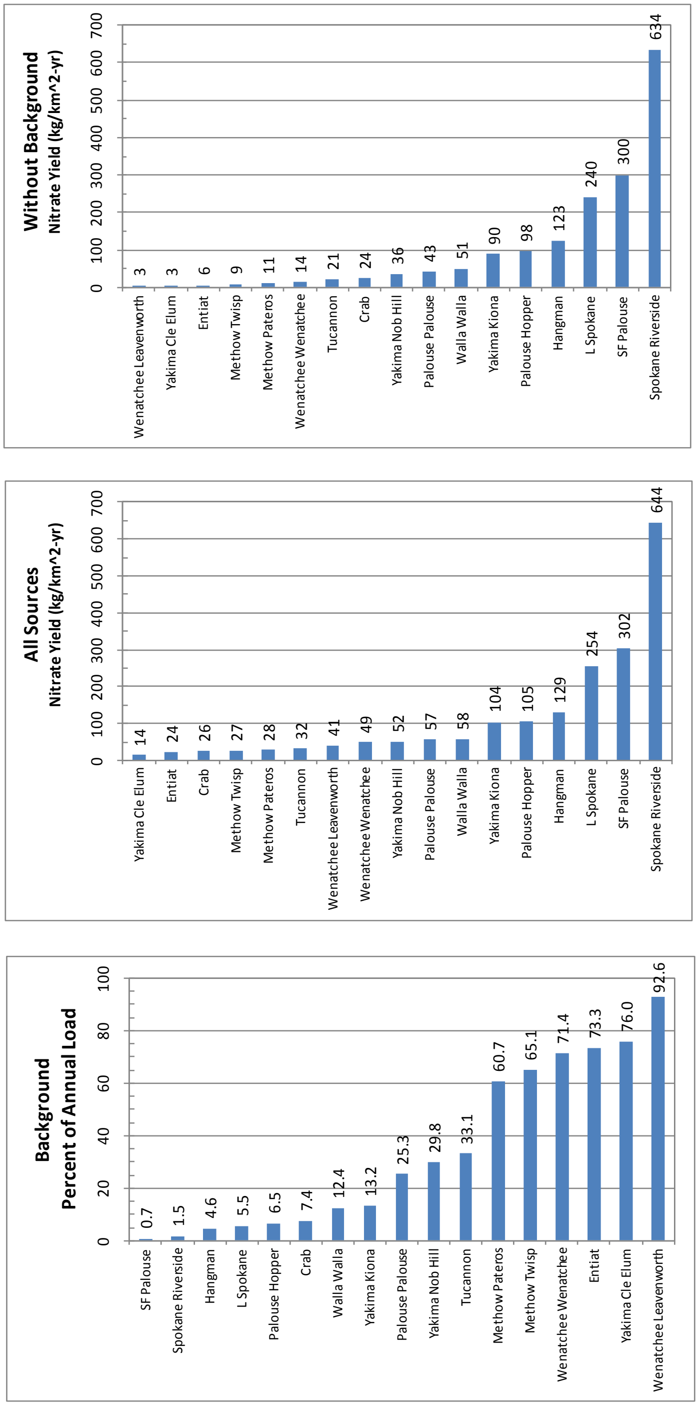

Figure 12. Estimated nitrate yields considering all sources, with and without background, eastern watersheds.

The migration pathway associated with dairy waste is a combination of groundwater infiltration (with eventual discharge to surface water) and direct surface runoff. The lower Yakima is now a center of dairy production in eastern Washington and because it is considerably drier in comparison to northeastern Whatcom County – the state's western center for dairy production- with a precipitation level of 0.21 meters per year as opposed to 1.22 m/yr, the primary pathway for nitrate export is infiltration to groundwater with eventual discharge to the Yakima River. The combination of high animal densities (per operation), climatic and geologic factors, has resulted in elevated localized groundwater nitrate concentrations to levels exceeding the drinking water standard of 10 mg/L. The connection between nitrate sources and loading levels will be examined in greater detail in the following section.

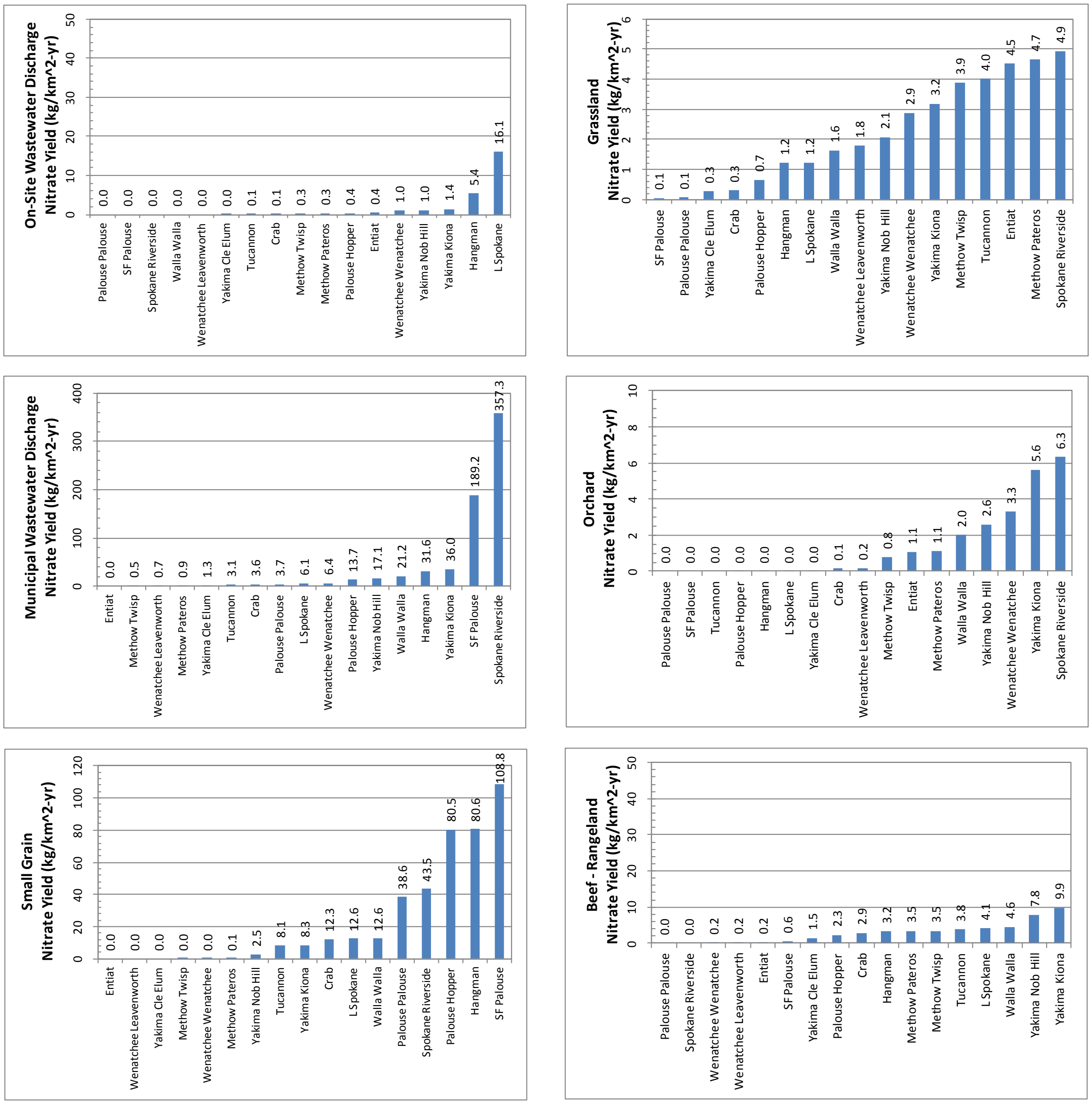

Figure 13. Estimated nitrate yields by source-type, excluding background sources, eastern Washington study watersheds (a).

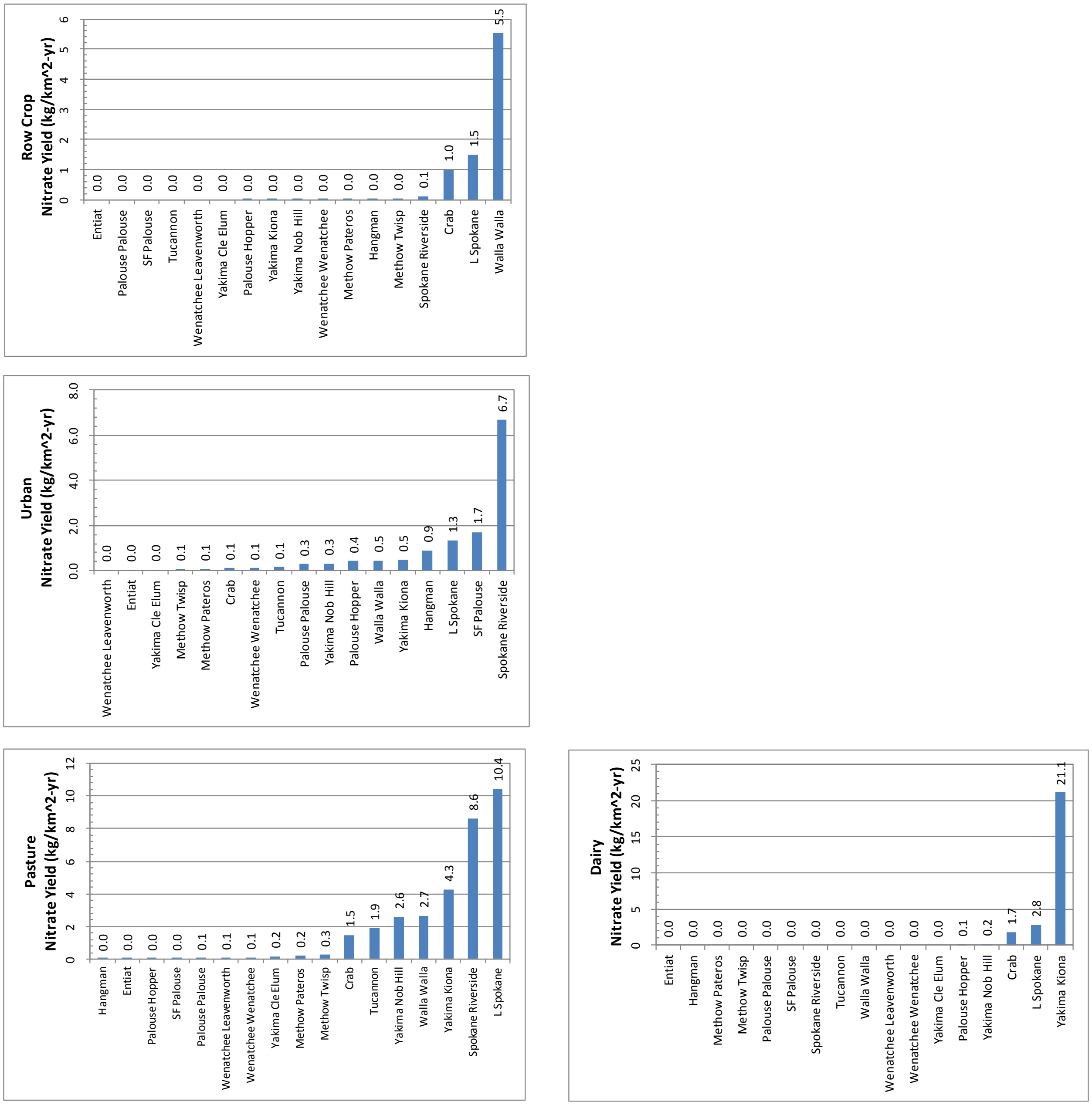

Figure 14. Estimated nitrate yields by source-type, excluding background sources, eastern watersheds (b).

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Application of Method

The effect of nitrate surface loading on groundwater

The prior analysis did not specifically account for the portion of the nitrate load observed at the surface water monitoring locations attributed to groundwater discharge. Instead, it assumed that the nitrate flow pathways, whether surface runoff, interflow, or groundwater, are ultimately accounted for at the monitoring location given the annual time frame considered. However, the portion of the nitrate transferred to groundwater is a public health interest because groundwater serves as the primary drinking water source for a significant portion of the state's population. The contamination of groundwater with nitrate has been a source of concern due to its potential adverse effect on human health and has been an issue in both the Nooksack and Yakima River watersheds in particular. Therefore, an analysis method was applied to the study data to provide an estimate of the connection between land surface-based nitrate loading and its effect on underlying groundwater concentrations.

Within this section, initially, general patterns in nitrate groundwater concentrations, observed within the study watersheds, are characterized. This information is used to construct a generalized model applied to examine the relationship between land surface nitrate loading and underlying shallow groundwater concentrations.

Implicit in this analysis is that a fraction of the nitrate load associated with land-based sources migrates to groundwater and that an equilibrium condition has been reached in the watersheds between loading inflows and outflows. That is, a shallow groundwater nitrate concentration has been reached reflective of long-term surface loading.

Analysis methods

The relationship between nitrate loading and its effect on underlying groundwater concentrations was examined though the following methods:

- The annual land-based nitrate load (expressed as a net yield) was estimated for each of the study drainages. The land-based load excludes the loading associated with point source discharge to surface water, though the load attributed to land surface application of municipal wastewater, if present, was included. It is the portion of the total net nitrate yield leaving the watershed derived from land sources. (In addition, a finer spatial delineation of loading was completed for the Yakima, Crab, and Nooksack watersheds, based on the prior methods, though applied at a hydraulic unit code (HUC) 10-scale. The case of the Yakima is presented later in this report, while the results for the Nooksack, Crab and Sumas are included in Appendix E).
- Nitrate loss through surface water storage was not applied to the net loading estimates. This is because nitrate associated with surface runoff directed to reservoirs undergoes physical, chemical, and biological attenuation processes, while nitrate infiltrated to groundwater, up-gradient of storage, circumvent these processes. The total surface area of open water present within a watershed was, however, subtracted from the overall drainage area total when calculating loading yields.

- Percentiles of shallow groundwater nitrate concentrations were determined for each of the study drainages based on the average of historic measurements recorded by the Washington State Departments of Health and Ecology, and the United States Geologic Survey, by well location. Shallow groundwater is defined here as samples collected from wells with depths less than 30-meters below land surface. Concentration percentiles were only generated if at least 15 monitoring wells were present within an assessment area.

The groundwater nitrate data used for this analysis are not unbiased. There are well samples collected from areas of concern (i.e. locations of known or suspected drinking water contamination), and the wells are not uniform in distribution throughout each of the watersheds, nor entirely screened and sampled from common strata, though short of a designated sampling effort, these are common groundwater type analysis limitations. In addition, the groundwater samples tended to be concentrated to the lower valleys where there is more intensive land management. Therefore, the effect of surface loading on groundwater nitrate concentrations is biased toward more elevated levels, given the context of an overall drainage area assessment. While this is a spatial bias, it is more reflective of the groundwater quality in proximity to where the majority of the nitrate loading actually occurs.

Study area shallow groundwater nitrate concentrations

Percentiles of shallow groundwater nitrate concentrations for the eastern and western study watersheds are presented in Figures 15 and 17, and Tables B-10 and 11 in Appendix B. Not all of the watersheds are represented due to the low number of monitoring wells (<15) present within them.

Western Washington watersheds

Referring to Figure 15, considering the western Washington watersheds, there are three general patterns to the concentration percentiles.

One of the patterns include drainages where the groundwater is relatively un-impacted by excessive nitrate surface loading. These drainages are characterized by low concentrations that are relatively uniform throughout the distribution. Watersheds fitting this pattern include the Nooksack @Cedarville, and the Skykomish. (It will be discussed later that groundwater nitrate concentrations in the Nooksack watershed increase significantly further down the valley from the Cedarville monitoring location.)

Another common pattern is characterized by watersheds with low overall groundwater nitrate levels, though having locations where more elevated concentrations have been observed. This situation applies to the majority of the stations to varying degrees. The lower the percentile level where the concentration shift occurs, and its ultimate extension, provides a useful diagnostic on the overall impact of land surface loading on underlying groundwater. For instance, consider the Cowlitz and Stillaguamish @Silvannia, while both have similar groundwater nitrate levels through the 60th percentile, they follow divergent paths at higher percentiles. At the 80th percentile, indicating that 20% of the observed groundwater concentrations were greater than this level, the Cowlitz nitrate level is 1.1 mg/L, while the Stillaguamish @Silvannia is 2.7 mg/L. Drainages having larger areas of impact include, in addition to the Stillaguamish @Silvannia, the Nisqually, and the South Fork (S.F.) Stillaguamish @Arlington (Figure 15). The Puyallup watershed has some of the highest nitrate levels, though observed at a low level of representation, indicating that the extent of groundwater contamination is relatively confined within the watershed.

The last pattern is depicted by a shift to higher nitrate concentrations at significantly lower percentiles indicative of a watershed where surface nitrate loading is both elevated and widespread with a corresponding effect on underlying groundwater. Among the western Washington watersheds examined this situation applies to the Deschutes drainage. While for the majority of the stations the separation in groundwater concentrations occurs at about the 60-70th percentile, for the Deschutes the concentration separation from the other stations occurs at the 20th percentile, indicating higher magnitude concentrations found over a greater spatial extent.

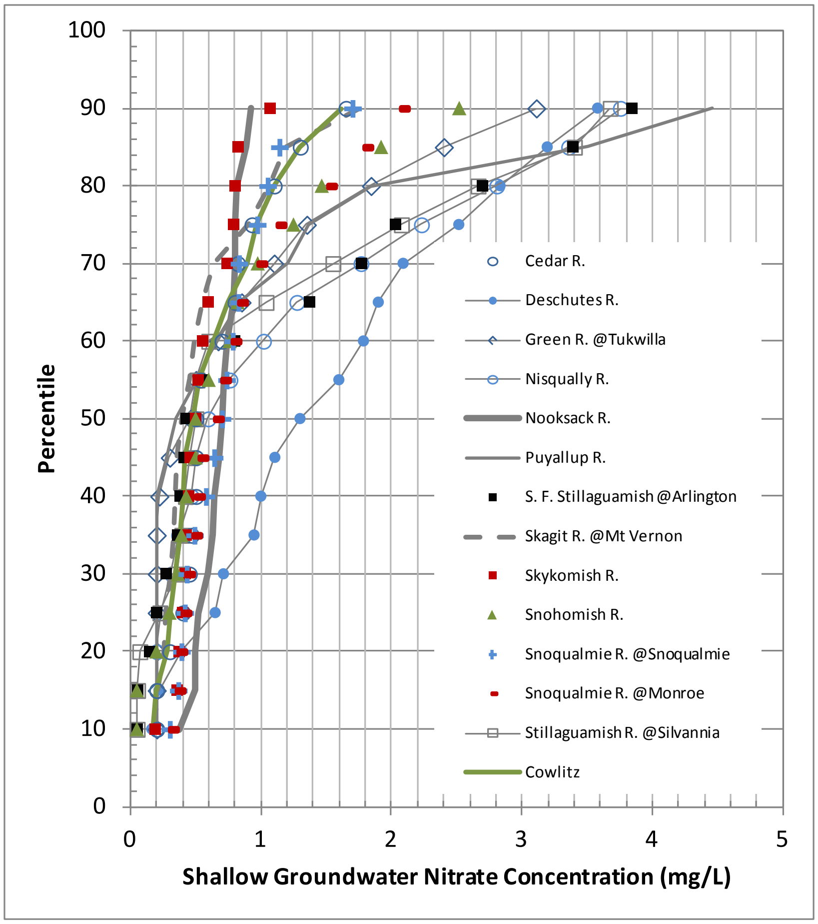

Figure 15. Percentiles of nitrate concentrations observed in shallow groundwater for the western Washington watersheds.

The land-based net nitrate yield for each of the western Washington watersheds is presented in Figure 16. At the extremes, the Samish and Deschutes have the greatest yields at 737 and 697 kg/km^2-yr, respectively, and a major reason for the Deschutes high overall groundwater concentrations. (The well network for the Samish was too low to generate percentiles.) The dominant nitrate sources within the Deschutes watershed include: pasture (32% of the loading yield), on-site (19%), poultry (16%), and beef (13%).

Evident from Figure 15, for the majority of the western Washington study drainages, groundwater nitrate levels are relatively low but there are areas within many of them that indicate the occurrence of groundwater impacts associated with surface nitrate loading. The reason for the lower groundwater concentrations is that many of the drainages have fairly common loading levels which are not that far removed from the estimated background level. Thirteen of the 29 study watersheds have an estimated annual nitrate loading yield less than 400 kg/km^2-yr, about 50% above the estimated background level. It is only at the extreme, for the Deschutes (180% above background) where the effect of elevated surface nitrate loading on groundwater concentrations becomes more apparent.

The net land-surface nitrate yield in the Puyallup is 43% lower than the Deschutes, yet has higher concentrations at the upper percentiles. As indicated, this has to do with the type and intensity of land use practices in proximity to the sampled groundwater wells. There is not wide spread nitrate groundwater contamination throughout the watershed, but there are areas where land use activities are clearly effecting groundwater nitrate levels. The case of the Deschutes watershed is different. It appears the combination of soils and geologic characteristics that affect the level of infiltration along with elevated and dispersed surface nitrate loading has led to watershed-wide elevated groundwater nitrate concentrations.

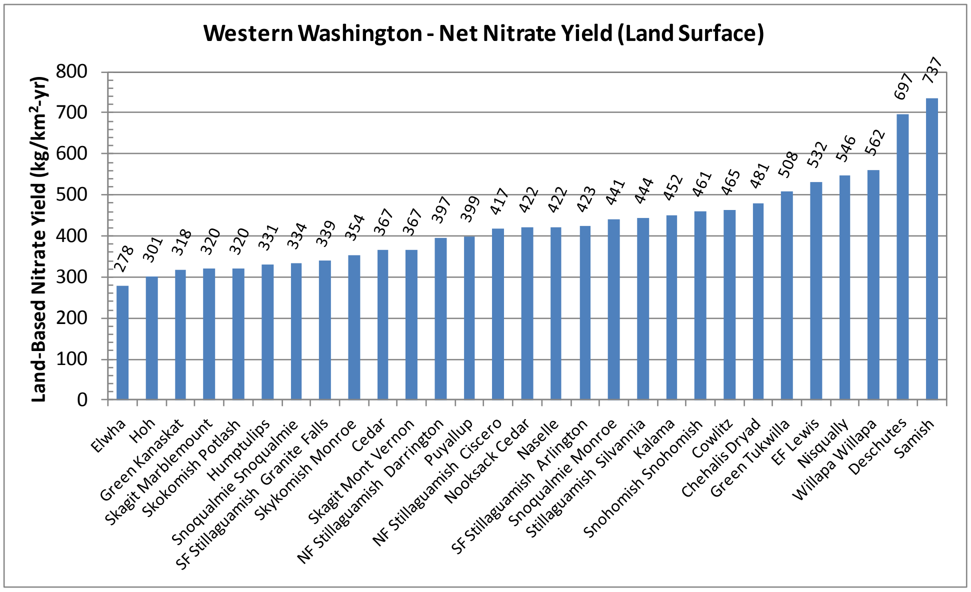

Figure 16. Net land surface nitrate yields for western Washington watersheds.

Eastern Washington watersheds

Eastern Washington groundwater is impacted to a greater extent both in terms of the area affected, and the magnitude of the nitrate concentrations observed, in comparison to western Washington (Figure 17). (Note difference in concentration scales between eastern and western Washington locations.) Despite these differences, similar groundwater nitrate percentile patterns, observed for the western Washington drainages, are also present for the eastern Washington drainages.

Nitrate groundwater concentration profiles indicative of only minor effects of surface loading include those of the Yakima @Cle Elum, Entiat, Wenatchee @Leavenworth, and the Methow @Pateros. The 85th percentile concentration among these stations ranges between 0.5 mg/L (Yakima @Cle Elum) to 1.5 mg/L (Methow @Pateros). The overall land-based nitrate yield for these stations is not much higher than what was assumed as a background loading level (Figure 17). From here there are varying degrees to the extent and level of impact.

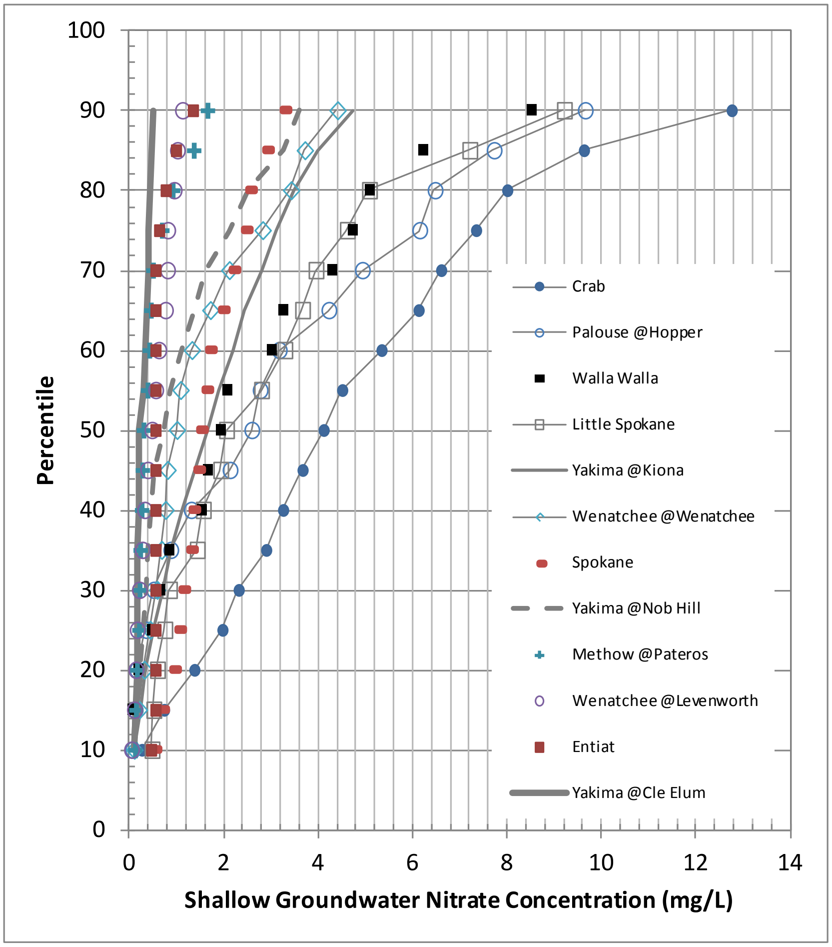

Figure 17. Percentiles of nitrate concentrations observed in shallow groundwater for the eastern Washington watersheds.

For the western Washington drainages the greatest separation in concentrations for the majority of the study drainages occurred at about the 70th percentile level. For the eastern Washington drainages, the separation occurs much lower, at about the 40th percentile level, indicating a greater spatial extent of groundwater impact. In addition, the level of impact, in terms of the magnitude of nitrate concentrations observed, is considerably greater in comparison to the western Washington drainages. The Little Spokane River, Walla Walla, Palouse @Hopper, and Crab Creek, in particular, all have profiles indicating extensive impacts to groundwater (Figure 17). The 85th percentile for these stations ranged from 7.2 mg/L (L. Spokane River), to 9.6 mg/L (Crab Creek). The transitional group includes: Yakima @Nob Hill and Kiona, Spokane

@Riverside, Wenatchee @Wenatchee, and Hangman Creek. The 85th percentile for this group has a range between 3.3 mg/L (Yakima @Nob Hill) to 4.0 mg/L (Yakima @Kiona).

While these figures provide a useful diagnostic assessment among the drainages, their size and particularly a monitoring network that documents the varied distribution of nitrate loading, are important considerations in interpretation. For instance, consider the Yakima River; there is a progression in increasing groundwater nitrate concentrations from the upper (Cle Elum), to the central (Nob Hill), and lower (Kiona), watershed. That nitrate concentrations increase with increasing drainage area indicates that the lower valley has the greatest nitrate groundwater concentrations. But the actual magnitude of the lower valley groundwater concentrations is diluted, to a great extent, by incorporating into the analysis, monitoring that occurred in the upper relatively un-impacted portions of the watershed. This indicates the utility of applying a more focused approach to the loading analysis if the emphasis is on understanding the connection between land uses, the surface nitrate loading associated with them, and the underlying groundwater quality. (The next section uses a focused loading analysis for the Yakima.) It is less a problem with the examination of surface water concentrations.

The Yakima watershed is somewhat unique due to the major changes in land use from its upper portions, which are mountainous and forested and relatively pristine from a nitrate loading perspective, to the agriculturally-managed lower valley where elevated nitrate concentrations in groundwater are an acknowledged major health concern. A similar situation also applies to the Nooksack watershed. In comparison, land use in the Crab Creek watershed, while also dominated by various agricultural land uses, is more uniformly distributed throughout the watershed and, therefore, so is the associated nitrate loading which is reflected in the concentration profile for the watershed. If the observed nitrate concentrations in the lower Yakima valley were examined in isolation, then a concentration distribution similar to that generated for Crab Creek would be the expected result.

The eastern Washington land-based nitrate yields observed for the drainages are included in Figure 18. Drainages with the lowest groundwater concentrations tended to also have the lowest yields. This includes: the Entiat (24 kg/km^2-yr), Yakima @Cle Elum (45 kg/km^2-yr), and Wenatchee @Leavenworth (40 kg/km^2-yr). (The assumed background nitrate yield is 21 kg/km^2-yr, though a slightly higher yield of 44 kg/km^2-yr was assumed for the Yakima @Cle Elum, and the two Wenatchee stations, since their forests-lands have more in common with those of the west-side, as opposed to the more commonly encountered greater eastern Washington shrub lands.) And, as expected, most of the drainages with the highest groundwater nitrate concentrations also tended to have among the highest yields.

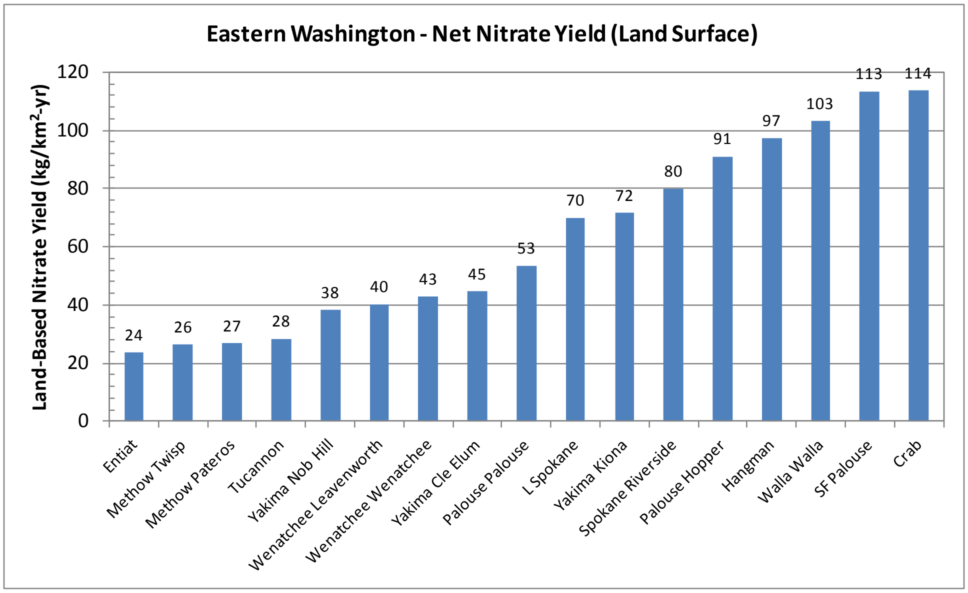

Figure 18. Net land surface nitrate yields for the eastern Washington watersheds.

Net land-surface nitrate loading yield and groundwater concentrations

Figure 19 displays the relationship between the net land-based nitrate yield (kg/km^2-yr), and the 65th percentile groundwater concentration observed for both eastern and western Washington watersheds. (The 65th percentile is approximately the average groundwater concentration.) Also included in the figure are results generated for the Yakima River, Crab Creek, and Nooksack watershed HUCs (the results and analysis for those watersheds are contained in the following report section, and Appendix E). Several HUCs in the lower Yakima valley were not included in this assessment and the reason why is discussed in a later section of the report. As mentioned earlier, this loading yield is calculated through the summation of the land-based nitrate sources within a watershed, excluding those associated with point sources and storage-related losses.

Calculated this way, the yield represents the net level of nitrate leaving each watershed by surface water derived from up-gradient land-based sources. Therefore, the watershed yield is a surrogate of the actual portion derived from groundwater discharge since a significant amount is also derived from direct surface runoff. Important to note here is that despite these additional nitrate flow pathways, there is proportionality between the net nitrate yield and associated up-gradient groundwater nitrate concentrations.

Eastern Washington drainages were found to have significantly greater groundwater nitrate levels, through similar ranges in loading, in comparison to those observed for western Washington, indicating the vulnerability of groundwater to contamination for much of the state's eastside. For eastern Washington, a net nitrate loading level of about 230 kg/km^2-yr results in a 65th percentile groundwater concentration, right at the maximum contaminant level (MCL) for drinking water of 10 mg/L. From Table 8, typical net nitrate export levels associated with row crops (280 kg/km^2-yr), orchards/vineyards (240 kg/km^2-yr), and small grain (130 kg/km^2-yr), result in 65th percentile (i.e. average) groundwater levels of between 6 and 12 mg/L. In comparison, a net nitrate loading level of about 3,100 kg/km^2-yr is required to reach a 65th percentile nitrate groundwater level of 10 mg/L within western Washington, 14 times greater than eastern Washington. The greatest nitrate export coefficients were found for row crops, orchards, and pasture, all at a level around 2,000 kg/km^2-yr.

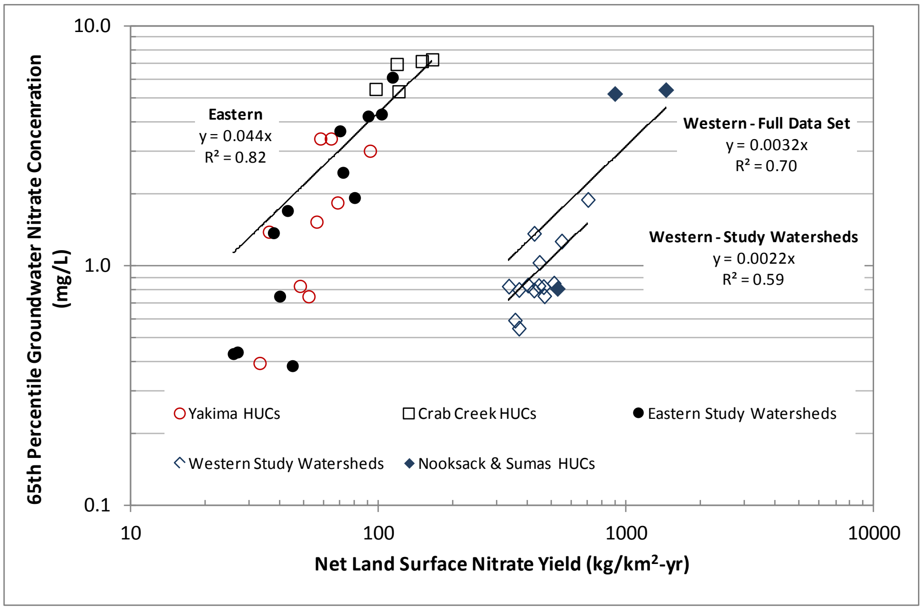

Figure 19. Relationship between net land surface nitrate yield and groundwater concentrations.

Alders in western Washington with a net nitrate export level estimated at 1,000 kg/km^2-yr could raise the underlying shallow groundwater to approximately 3.2 mg/L, based on Figure 19. However, scale is an important consideration in the application of these relationships. Nitrate source types, and their extent within a designated analysis area, are important factors to consider in evaluating impacts to either groundwater or surface water quality.

Applying the forest net loading level (266 kg/km^2-yr) for western Washington, representative of a background loading condition, results in an average groundwater level of about 0.6-0.9 mg/L. For eastern Washington the background concentration for a net loading rate of 21 kg/km^2-yr is about 0.9 mg/L. This suggests that under natural loading conditions, expected groundwater nitrate concentrations were fairly similar for eastern and western Washington. With more intensive land management and associated increased nitrate loading, combined with a lower dilution level, has resulted in a greater extent of groundwater nitrate contamination throughout eastern Washington. (These assumed background concentrations will be slightly higher than actual, since many of the watersheds and HUCs with low estimated yields did not have a sufficient monitoring well coverage to be included in the analysis, introducing a slight upward bias.)

Groundwater Loading Model

A generalized model was used to examine the connection between net land surface nitrate loading and its effect on underlying groundwater. Two analysis processes were applied to the study watersheds based on their location, east or west of the Cascade divide. The reason for the regional separation is due to the influence of irrigation on recharge for a significant amount of the eastside study area. Fortunately, the United States Geological Survey (USGS) has modeled recharge levels for much of the eastern study area along with the production of ArcGIS grids of the estimates. Ultimately, the groundwater quality and recharge quantity were tied to the surface water nitrate yield by considering base-flow quality. A discussion of the methods and results follow, organized by region.

Western Washington

Flow Pathways

The relationship between mean annual precipitation, evapotranspiration, surface water outflow, and recharge was examined for several western Washington catchments. (Recharge is the portion of precipitation that migrates to groundwater contributing to its volume.) A basis of this analysis was derived, in part, from Bauer (1997-Table 1). The Bauer report contains a compilation of reported mean annual recharge levels for several small western Washington catchments in addition to annual evapotranspiration and precipitation rates. If available, discharge data were examined for the catchments and the annual surface outflow levels determined (http://waterdata.usgs.gov/wa/nwis/nwis). Only catchments that had a discharge record were considered. From the collective information, flow pathways relevant to this analysis were derived including: direct surface runoff (SR) and the portion of recharge that is discharged to surface water within the watershed (R_q).

The following series of equations were applied to estimate the split in the total net outflow attributed to groundwater discharge (R_q) and direct surface runoff (SR) in addition to the portion of recharge that is discharged beyond the watershed (R_d). (Definitions for the variables follow.)

Equation 1 $P-ET-R=SR$

Equation 2 $O=SR+R_q$

Equation 3 $R=R_d+R_q$

Equation 4 $P-ET-R_d=SR+R_q$

P=precipitation, ET=evapotranspiration, R= recharge, Rq=recharge that is discharged in watershed, Rd=recharge discharged beyond watershed, SR=surface runoff and interflow, O=surface outflow

Table 15 presents the magnitude of the hydrologic flow pathways characteristic of the western Washington catchments. Based on overall median values, the relative representation of the mean annual precipitation in relation to the various flow pathways was determined (Table 16).

Table 15. The magnitude of various hydrologic flow pathways for several western Washington catchments.

Catchment – USGS No.	DA (km^2)	P	ET	O	R	SR	R_q	R_d
		m/yr						
Evans - 12124000	33.6	1.03	0.50	0.59	0.34	0.20	0.39	===
North - 12126000	63.7	0.97	0.45	0.50	0.22	0.29	0.20	0.08
Swamp - 12127100	59.8	0.85	0.41	0.50	0.17	0.27	0.23	===
Woodland - 12081000	63.7	1.31	0.43	0.34	0.73	0.15	0.19	0.57
Clover - 12090500	191.1	1.03	0.44	0.19	0.37	0.23	===	0.42
median	**63.7**	**1.03**	**0.44**	**0.50**	**0.34**	**0.23**	**0.20**	**0.08**

DA=drainage area, P=precipitation, ET=evapotranspiration, R= recharge, Rq=recharge that is discharged in watershed, Rd=recharge discharged beyond watershed, SR=surface runoff and interflow, O=net surface outflow

Table 16. The relative representation of various flow pathways as they relate to the annual average precipitation for several western Washington catchments (a).

E:P	SR:P	O:P	R:P	R_d:P	R_q:P
0.42	0.25	0.48	0.33	0.10, (0.29R)	0.23, (0.71R), 0.48O)

P=precipitation, ET=evapotranspiration, R= recharge, Rq=recharge that is discharged in watershed, Rd=recharge discharged beyond watershed, SR=surface runoff and interflow, O=net surface outflow

Based on these relationships, about 33% of the annual precipitation serves as recharge in western Washington. Of the total recharge, about 70% is ultimately discharged within the catchment (R_q), effectively comprising about 23% of the annual average precipitation, with 30% discharged to the larger regional aquifer (R_d).

For the western Washington study watersheds, the net surface water outflow is approximately 60-70% of the mean annual precipitation, a slightly higher level than found for the catchments (refer to Appendix B, Table B-1). This difference is believed attributed to the storage of winter precipitation in the form of snow for many of the study watersheds. This results in a redistribution in the representation of the flow pathways (i.e. ET declines while net outflow increases). The catchments examined by Bauer are all relatively small with minimal relief and, therefore, experience little, if any, winter snow accumulation.

Vaccaro (1997) estimated that about 51% of the mean annual precipitation contributes to recharge in the greater Puget Sound aquifer system. Table 17 presents the various flow pathways expressed as a representation of the annual average precipitation assuming typical evapotranspiration rates for western Washington (~ 0.5 m/yr), and that net surface outflow and recharge represent about 68% and 51% of the annual precipitation, respectively.

Based on the factors presented in Table 17, the amount of the total annual recharge that is typically discharged to surface water (within the watershed in which it originally infiltrated) is around 75% with 25% flowing to the deeper regional aquifer system (discharges beyond the watershed). So despite the changed assumptions, this split in the recharge flow pathways is close to the 70/30 split previously estimated (refer to Table 16). Groundwater discharge comprises about 56% of the net annual surface outflow with the remainder attributed to direct surface runoff and shallow interflow.

Table 17. The relative representation of various flow pathways as they relate to the annual average precipitation for western Washington watersheds (b).

E:P	SR:P	O:P	R:P	R_d:P	R_q:P
0.19	0.30	0.68	0.51	0.13, (0.25R)	0.38, (0.75R), 0.56O)

P=precipitation, ET=evapo-transpiration, R= recharge, Rq=recharge that is discharged in watershed, Rd=recharge discharged beyond watershed, O=surface runoff and interflow

Generalized Loading Model

The association between the net land-based nitrate yield (in units of kg/km^2-yr), the level of recharge, and their combined effect on underlying groundwater concentrations was examined through the application of a simple model (Equation 5). In this model, the net land surface nitrate yield (Y) serves as a reference with a loading factor applied to it reflecting the relative level of mass transfer to groundwater. The groundwater concentration is then determined based on the level of recharge associated with the nitrate load. The net nitrate yield is used since this metric is central to this study's overall analysis and that it can be generated from nitrate and flow data typically collected as part of routine watershed (outlet) monitoring, increasing the accessibility and utility of the described methods in their application. (Note: point source and storage influences on the yield must be considered.)

Equation 5

$$\frac{Y*(L.F.)*1000}{R} = [NO_3^-{}_{gw}]$$

Y=estimated net land surface load yield (kg/km^2-yr)
LF=load factor
R =Recharge, (0.33 to 0.51)*annual average precipitation (m^3/km^2-yr)
$[NO_3^-{}_{gw}]$ = 65th percentile groundwater nitrate concentration (mg/L)

Based on the results presented in Tables 16 and 17, it's assumed that the annual average recharge volume lies somewhere between 33-51% of the mean annual precipitation. For the western Washington study watersheds, the midpoint (43%) corresponds to an equivalent volume of 62% of the net surface outflow (Figure 20). The groundwater nitrate concentration is represented by the 65th percentile observed among the shallow (<100m) wells present within each study watershed, given sufficient data (n>15). The yield factor is based on each watershed's estimated net land surface nitrate load. Only the loading factor (LF) remains an unknown and so serves as the calibration variable between observed and predicted groundwater nitrate concentrations.

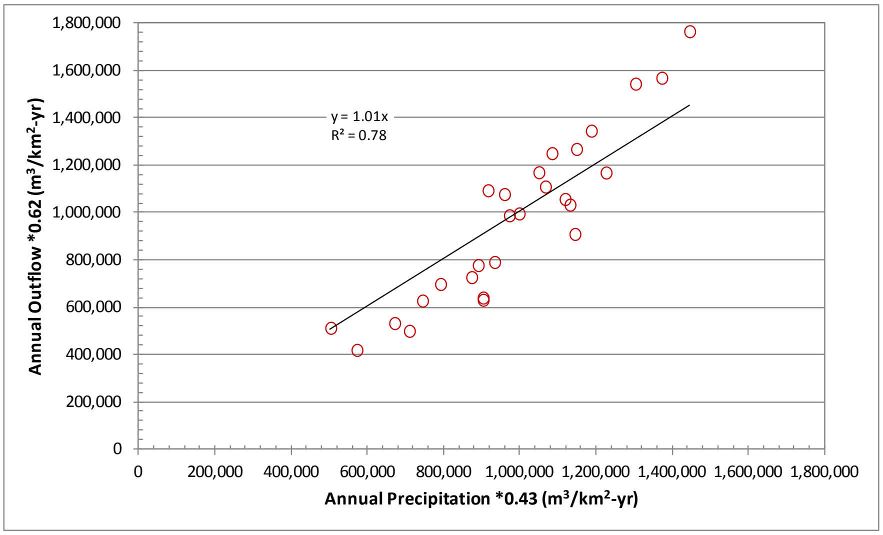

Figure 20. Relationship of precipitation and surface outflow as expressions of recharge (R).

Calibration and Results

The load factor that provides the best fit between measured and predicted groundwater nitrate, assuming the mid-point for recharge equivalent to approximately 43% of the annual precipitation, is 2.1 (Equation 6, Figure 21).

Equation 6

$$\frac{Y\,(2.1)*1000}{P\,(0.43)} = [NO_3^-{}_{gw}]\ (mg/L)$$

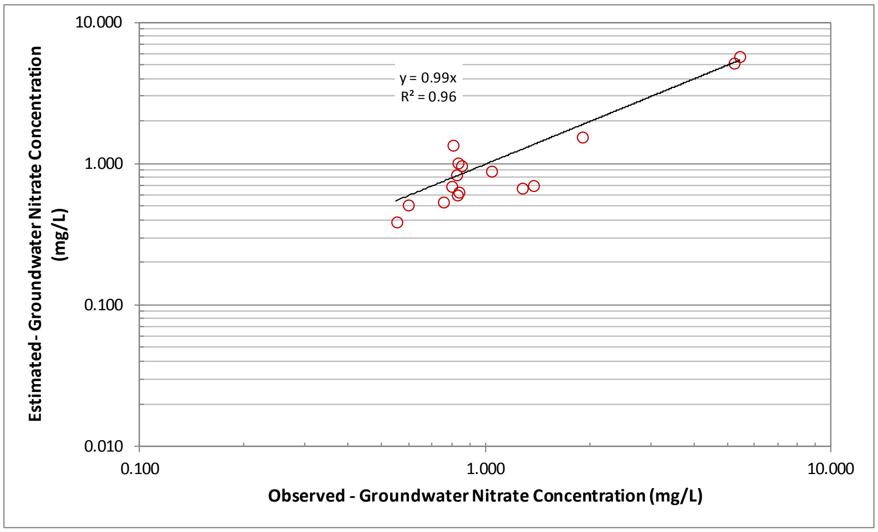

Figure 21. Relationship between observed and predicted groundwater nitrate concentrations, western Washington watersheds.

Referring back to Figure 19, for the western Washington watersheds, the best fit coefficient (slope) relating the net land-based nitrate yield to the 65th percentile groundwater concentration was 0.0022. Among the study watersheds, the overall median of the terms on the left hand side of the equation 1000*2.1/(R~0.43P), as they relate to Y, results in a factor of 0.0021 (median overall R=997,600 m^3/km^2-yr, ~1.0 m/yr), providing context to the regression relationship.

The Base-Flow Condition

Groundwater serves as a primary source of flow during the August-September period for western Washington surface waters. This is referred to as the base-flow period. It is assumed here that base-flow is entirely derived from groundwater discharge and that its quality, as observed at the outlet monitoring locations, reflects an integration of its varying quality occurring throughout the watershed. However, it is recognized that this assumption is not always true for many of the western Washington study watersheds. Exceptions include systems with high elevation snow and glacial melt (i.e. Hoh River) and those with reservoirs. For these cases the actual groundwater quality is diluted at base-flow. Also requiring consideration are surface waters where nitrate concentrations are highly influenced by point source discharge. The annual low flow tends to occur during the base-flow period and point source discharge has its greatest effect on in-stream nitrate concentrations at this time. Because of these factors, several of the study watersheds were removed from consideration since the objective of this analysis is to better understand the interaction of land surface nitrate loading and its effect on underlying groundwater. It's assumed, despite these "exceptions", that fundamentally all watersheds share a similar underlying dynamic between surface loading, recharge, and their combined effect on shallow groundwater nitrate concentrations.

Assuming that about 43% of the mean annual precipitation serves as recharge and of that about 70% is ultimately discharged to surface water within the watershed. Therefore, the level of recharge ultimately contributing to surface flow is equivalent to about 30% of the mean annual precipitation or a level that is equivalent to about 44% of the net surface water outflow (Figure 22). This annual groundwater discharge estimate when multiplied by the base-flow nitrate concentration provides an estimate of the net annual groundwater-derived load discharged to surface water, accounting for attenuation. Among the western Washington study watershed's, this net groundwater-based annual load comprises about 26% of the total load (18%-47%), considering all sources, with the remaining 74% associated with direct land surface runoff.

Important with understanding the effect of surface nitrate loading to groundwater, is determining what level of attenuation is expected to occur during the flow path from infiltration to its eventual flow from the watershed. An approximation of a watershed-scale nitrate attenuation level was determined from the ratio of the base-flow nitrate concentration (August-September average), divided by the 65th percentile groundwater concentration. The ratio provides a representation of the concentration of groundwater, following discharge (base-flow), relative to its prior level within shallow groundwater. This ratio, or representation of loss, was calculated for each of the study watersheds with sufficient groundwater quality data (>15 wells). The results are presented in Figure 23, with the attenuation levels presented as percent loss.

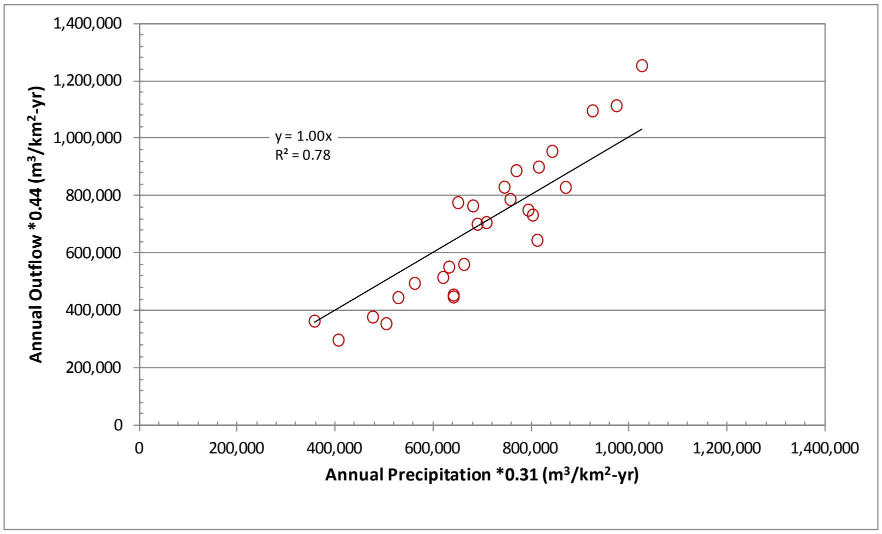

Figure 22. Equivalency of R_q expressed as precipitation and surface outflow.

Results indicate that there is a significant decline in the nitrate concentration between levels observed in groundwater, and at base-flow. This relationship applies to both western and eastern watersheds through varying hydrologic conditions and loading levels.

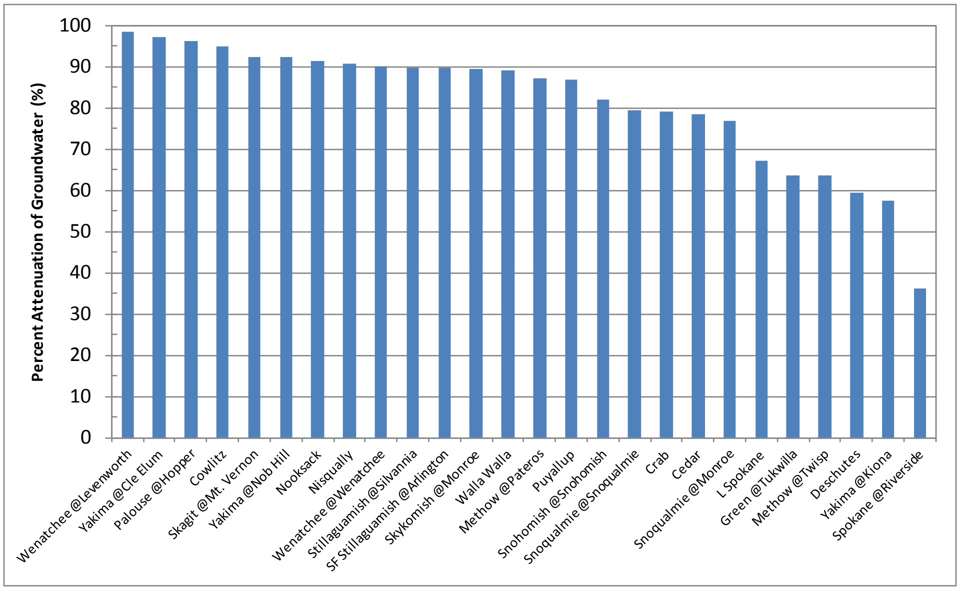

Figure 23. Percent reduction in nitrate concentrations between the 65th percentile groundwater concentration and those observed at base-flow.

The highest attenuation levels are found for the study watersheds with storage. This applies to the Wenatchee @Leavenworth, Yakima @Cle Elum, Cowlitz, and the Skagit @Mt. Vernon. (The exception is the Palouse @Hopper.) For these stations the true expression of the base-flow nitrate concentration is obscured by the release of flow from storage, reducing its concentration and resulting in elevating the estimate of attenuation. The median level among these stations is 96%.

At the other end, for attenuation rates below about 87% (Puyallup), the base-flow nitrate concentrations are affected by factors that elevate base-flow nitrate concentrations, effectively reducing the estimated attenuation levels. Among this group, at the most extreme, with an attenuation of 36% is the Spokane River @Riverside where its base-flow discharge nitrate concentration is highly influenced by the city's WWTP discharge. This situation also applies to the Methow @Twisp. (The effect of the WWTP discharge is diminished by the lowest reach at Pateros.) For these stations, there is a significant enough source and flow pathway for the delivery of nitrate during base-flow that disrupts the more typical groundwater/base-flow nitrate relationship.

Based on this method, an overall level of groundwater nitrate attenuation for the majority of the watersheds is high, conservatively around 70-80%. Therefore, on average, based on this finding and assuming minimal storage and point source influences, then the base-flow nitrate concentration is approximated by applying 0.3-0.2 (70-80% attenuation) to the 65th percentile watershed groundwater concentration (Equation 7). Based on this finding, Equation 6 can then be modified to solve for the base flow nitrate concentration (Equations 8 and 9) tying the net yield back to a surface water reference.

The flow component was set at 0.43Q, reflecting the amount of total recharge occurring within the watershed that is ultimately discharged to surface water (R_q). This flow comprises about

70% of the total recharge. Therefore, about 70% of the 2.1Y transferred to groundwater is discharged to surface water (to maintain the estimated groundwater concentration) comprising a net transfer of about 1.5Y. It was previously mentioned that the typical proportion of the annual nitrate load associated with groundwater discharge was about 26% for western Washington watersheds. Therefore, the typical attenuation factor is about 83% resulting in a 17% net transfer of groundwater-derived nitrate observed at the outlet monitoring location. Figure 24 presents the relationship between observed and estimated base-flow nitrate concentrations based on these factors.

Equation 7 $[NO_{3\,gw}^{-}] *\sim 0.2\text{-}0.3 = [NO_{3\,bf}^{-}]$

$[NO_{3\,gw}^{-}]$ = *groundwater nitrate concentration (mg/L)*
$[NO_{3\,bf}^{-}]$ =*base-flow nitrate concentration (mg/L)*

$$[NO_{3\,gw}^{-}] = \frac{[NO_{3\,bf}^{-}]}{\sim 0.2\text{-}0.3}$$

Equation 8

$$\frac{Y\,(2.1)*(0.7)*(1000)}{Q\,(0.62)*(0.7)} = [NO_{3\,gw}^{-}]$$

R =Recharge, (0.62*Q, m^3/km^2-yr)

Equation 9

$$\frac{Y\,(1.5)*(1000)}{Q\,(0.43)} = \frac{[NO_{3\,bf}^{-}]}{0.17}$$

$$\frac{Y\,(0.26)*(1000)}{Q\,(0.44)} = [NO_{3\,bf}^{-}]$$

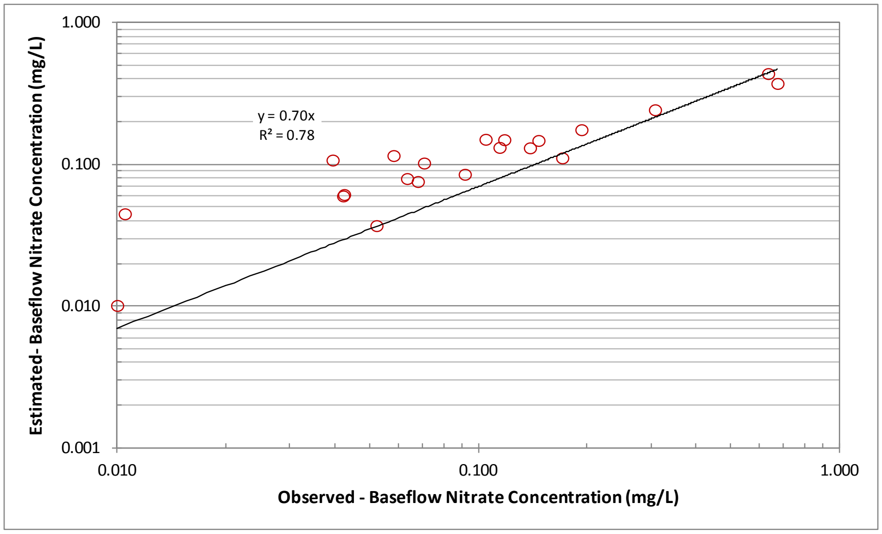

Figure 24. Relationship between observed and predicted base-flow nitrate concentrations, western Washington locations.

In review, of the total effective load transferred to groundwater, estimated at 2.1Y, only 0.3Y is ultimately observed at the monitoring locations. The total effective yield is comprised of the 2.1Y transferred to groundwater and the 0.7Y associated with direct surface runoff or a total of 2.8Y. Of that total, over 75% (2.1/2.8) is transferred to groundwater but, ultimately, due to high attenuation (~80%) only 0.3Y is observed at the watershed outlet. Together, this indicates a disproportionate effect of the land surface nitrate load on groundwater in comparison to surface water underlining its high vulnerability to contamination.

The data inputs to equations along with results are included in Table 18.

Table 18. Overview of model input data and results for the western Washington study areas.

Analysis Areas		O (m/yr)	R (m/yr)	R_q (m/yr)	Y (kg/ km^2-yr)	2.1*Y (kg/ km^2-yr)	Est. GW Nitrate (mg/L)	Obs. GW Nitrate (mg/L)	Est. BF Nitrate (mg/L)	Obs. BF Nitrate (mg/L)
Core Western Washington Watersheds	Chehalis	1.031	0.903	0.454	502	1055	1.168	===	0.288	===
	Cowlitz	1.124	0.791	0.494	204	428	0.541	0.753	0.107	0.040
	Deschutes	0.675	0.572	0.297	425	892	1.559	1.900	0.372	0.674
	E. F. Lewis	1.253	0.890	0.551	456	957	1.075	===	0.215	===
	Elwha	1.465	1.144	0.645	25	53	0.046	===	0.010	0.010
	Green @Kanaskat	1.016	0.903	0.447	130	273	0.303	===	0.076	0.068
	Green @Tukwila	0.804	0.710	0.354	330	694	0.978	0.850	0.243	0.309
	Hoh	2.846	1.445	1.252	216	453	0.314	===	0.045	0.011
	Humptulips	2.529	1.372	1.113	361	759	0.553	===	0.084	===
	Kalama	1.274	0.933	0.560	425	892	0.956	===	0.197	===
	Naselle	2.044	1.148	0.899	998	2095	1.825	===	0.288	===
	NFStill. @Cicero	2.015	1.084	0.887	393	826	0.763	===	0.115	0.058
	NFStill. @Darrington	1.664	1.131	0.732	240	503	0.445	===	0.085	0.092
	Nisqually	0.857	0.671	0.377	217	455	0.678	1.274	0.149	0.118
	Nooksack	1.762	0.916	0.775	305	640	0.699	0.796	0.102	0.071
	Puyallup	1.011	0.744	0.445	225	473	0.636	0.835	0.132	0.115
	Samish	0.825	0.503	0.363	610	1280	2.545	===	0.437	0.635
	S. F. Still.@Arlington	1.703	1.118	0.749	377	792	0.708	1.372	0.131	0.139
	S. F. Still. @Granite Falls	2.489	1.303	1.095	252	530	0.407	===	0.060	0.042
	Skagit @Marblemount	1.737	0.959	0.764	109	228	0.238	===	0.037	0.052
	Skagit @Mt. Vernon	1.885	1.049	0.830	196	411	0.391	0.552	0.061	0.043
	Skykomish	2.169	1.187	0.954	292	612	0.516	0.596	0.079	0.064
	Snohomish @Snohomish	1.604	0.998	0.706	400	841	0.843	0.822	0.147	0.147
	Snoqualmie @Monroe	1.592	0.972	0.700	473	993	1.022	0.830	0.176	0.193
	Snoqualmie @Snoqualmie	1.884	1.226	0.829	354	744	0.607	0.826	0.111	0.171
	Stillaguamish	1.788	1.066	0.787	455	955	0.895	1.038	0.150	0.105
	Willapa	1.170	0.873	0.515	893	1876	2.149	===	===	===
Nooksack HUCs	Lower NF Nooksack	0.702	0.736	0.438	479	1005	1.366	0.803	===	===
	Nooksack-Frontal	0.373	0.391	0.440	968	2033	5.201	5.222	===	===
	Sumas	0.500	0.524	0.252	1445	3035	5.789	5.420	===	===

O=net outflow, R=recharge, Rq=recharge discharged to surface water, 2.1Y relative nitrate load to groundwater within drainage area

Eastern Washington

Flow Pathways

Estimates of annual recharge occurring in the greater eastern Washington study area were derived from a United States Geological Survey (USGS)-generated grid based on results from a regional groundwater model (Ely, 2015). The eastern Washington areas considered included the study watersheds, and the Crab Creek and Yakima HUCs. The grid did not encompass all of the eastern Washington watersheds however and so the Wenatchee, Entiat, and Methow were not considered. The grid provided recharge estimates based on a 9-square kilometer (km^2) cell division. In sampling the grid, only cells intersecting the monitoring wells were considered as opposed to applying an entire watershed average (the approach used for western Washington). The reason for this is that many of the study areas have wide ranges in recharge levels reflecting whether irrigation is applied to the land in addition to widely varying geologic and topographic characteristics. Monitoring wells tended to be located within irrigated areas and, therefore, a watershed average approach would not reflect recharge levels in proximity to the actual monitoring wells. Based on the intersected data, by watershed or HUC, an overall median recharge level was determined.

The same model approach was applied to the eastern Washington study areas as used for western Washington though the input of recharge levels was direct as opposed to using surrogate measures. Again, calibration was achieved through adjustment of the loading factor.

Calibration and Results

Two load factors were determined for the eastern Washington study locations, one for the Yakima HUCs (2.8) and another for the study watersheds and Crab Creek HUCs (6.2). The loading factor differences reflect a lower effective nitrate transfer, for equivalent recharge levels, for the Yakima in comparison to the Crab Creek HUCs and the study watersheds. The Yakima load factor is about half that determined for Crab Creek. Figure 25 presents the relationship of the observed and estimated nitrate concentrations for the eastern study locations based on these loading factors with the overall data presented in Table 19.

Regarding the Yakima HUCs, several had considerably lower observed groundwater nitrate concentrations then expected based on the calibration (Figure 25). These include: Deep Canyon, Spring, and Simcoe; all are located in the lower valley. For these HUCs, a loading factor of 0.8 provides the best fit, a 71% reduction to the overall Yakima loading factor. Potentially for the lower Yakima overall and these locations in particular is that recharge (along with associated nitrate) may be intercepted by subsurface tile drainage before reaching shallow groundwater. This intercepted recharge is then discharged to the many waste-ways situated on the lower valley with eventually flow directed back to the Yakima River. Unfortunately, there is not sufficient monitoring well coverage of the mid and upper Yakima valley HUCs to explore this possibility further. (However, Taneum, located mid-valley (above irrigation) calibrates to the 6.2 loading factor.)

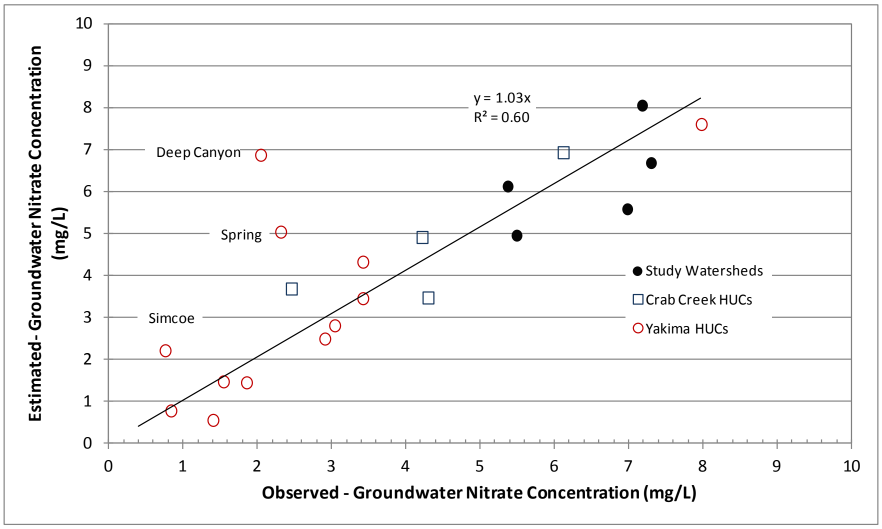

Figure 25. Relationship between observed and estimated groundwater nitrate concentrations, eastern Washington locations.

Referring back to Figure 19, for the eastern Washington watersheds, the best fit coefficient (slope) relating the net land-based nitrate yield to the 65th percentile groundwater concentration was 0.044. Considering all the Crab Creek and Yakima HUCs and the study watersheds, the overall median of the terms on the left hand side of the equation 1000*6.2 or 2.8/(R), as they relate to Y, results in a factor of 0.039 (median overall R=121,660 m^3/km^2-yr, ~0.121 m/yr), again providing context to the regression relationship. The relationship presented in Figure 19 assumes a relatively uniform recharge level throughout the analysis area.

The Base-Flow Condition

Unfortunately the Yakima and Crab HUCs (which together comprise the majority of the eastern analysis locations) do not have surface water quality monitoring associated with them. So the analysis of groundwater discharge quality is limited to just a few of the core study watersheds. And there are really not enough of them to properly analyze the association of groundwater to base-flow nitrate concentrations. Therefore, while a base model can be proposed, following from the approach used for the western Washington watersheds, it cannot be validated.

For the majority of the study watersheds (and HUCs), groundwater discharge comprises the vast majority of the net annual surface outflow. This applies primarily to drainages situated beyond the slopes of the eastern Cascades (i.e. not the Yakima). Based on the ratio of the net surface outflow and, in this case, watershed average recharge levels, about 43% of the recharge is discharged within the watershed (R_q) with the remaining 57% flowing to deeper regional aquifer systems (R_d). (Refer to Table 19 – the core study watersheds.) Assuming the same ratio applies to the Yakima, then the net outflow is comprised of about 34% groundwater discharge with the remaining 66% associated with surface runoff (includes reservoir discharge).

Previously it was noted that there are not significant regional differences in groundwater discharge net attenuation levels (as indicated by the concentration ratio of base-flow to 65th percentile groundwater). Given this, let’s assume that the net attenuation is similar to that determined for the western Washington study locations, 0.17. These assumptions are then applied to the study locations in Equations 10 and 11.

Crab Creek HUCs – Various Eastern Study Watersheds

Equation 10

$$\frac{Y*(0.43)*(6.2)*(0.17)}{R*(0.43)*(1000)} = [NO_3^{-}{}_{bf}]$$

R =Recharge, direct input (m/yr)

$$\frac{Y*(0.45)}{R*(0.43)*(1000)} = [NO_3^{-}{}_{bf}]$$

Yakima HUCs

Equation 11

$$\frac{Y*(0.43)*(2.8)*(0.17)}{R*(0.43)*(1,000)} = [NO_3^{-}{}_{bf}]$$

$$\frac{Y*(0.20)}{R*(0.43)*(1,000)} = [NO_3^{-}{}_{bf}]$$

Considering the Crab Creek HUCs (and study watersheds) overall there is an effective yield of 6.75Y; the groundwater associated load (6.2Y) and that associated with surface runoff (0.55Y). The transfer to groundwater then comprises 92% of the effective yield. Though following its discharge and accounting for net attenuation processes, groundwater comprises about 45% of the annual yield with direct surface runoff comprising the remainder (55%).

The overall effective yield for the Yakima HUCs is 3.6Y; the groundwater associated load of 2.8Y along with 0.8Y associated with surface runoff. The nitrate transfer to groundwater then comprises 78% of the effective yield though following its discharge and undergoing various attenuation processes results in groundwater discharge comprising about 20% of the annual yield with surface runoff comprising the remaining 80%.

Table 19. Overview of model input data and results for the eastern Washington study areas.

Analysis Areas		Recharge Estimate (m/yr)	Net Surface Outflow (m/yr)	Net Land Surface Nitrate Load (kg/km^2-yr)	Effective Load to Groundwater (kg/km^2-yr)	Est. Groundwater Nitrate (mg/L)	Obs. Groundwater Nitrate (mg/L)
Yakima HUCs	Ahtanum	0.1320	===	68	190	1.442	1.846
	Cle Elum	===	===	29	81	===	===
	Corral	0.0520	===	64	179	3.446	3.412
	Deep Canyon	0.1620	===	397	1,112	6.862	2.036
	Dry Creek	0.0060	===	41	115	19.133	===
	Kachess	===	===	33	92	===	0.395
	L Naches	===	===	35	98	===	===
	L Satus	0.0740	===	36	101	1.362	===
	Marion Drain	0.1510	===	134	375	2.485	2.900
	MF Teanaway	===	===	32	90	===	===
	Rattlesnake	===	===	37	104	===	===
	Simcoe	0.0660	===	52	146	2.206	0.750
	Spring	0.1230	===	221	619	5.031	2.306
	Sunnyside	0.1530	===	415	1,162	7.595	7.969
	Taneum	0.1840	===	36	101	0.548	1.394
	Tieton	0.1570	===	242	678	4.316	3.412
	Toppenish	0.1070	===	56	157	1.465	1.535
	Umtanum	0.0580	===	45	126	2.172	===
	U Satus	===	===	36	101	===	===
	Wenas	0.0940	===	48	134	1.430	===
	Wide Hollow	0.0920	===	92	258	2.800	3.033
	Wilson	0.1740	===	48	134	0.772	0.828
Crab Creek HUCs	Crab-Pothole	0.1219	===	97	601	4.933	5.490
	Frenchman	0.1526	===	164	1,017	6.661	7.300
	L. Crab	0.1316	===	118	732	5.561	6.980
	Round Lake	0.1220	===	120	744	6.098	5.370
	Winchester	0.1151	===	149	924	8.029	7.180
Study Watersheds	SF Palouse	0.1841	0.073	113	701	3.805	===
	Hangman	0.1107	0.068	97	601	5.431	===
	Crab Creek	0.1021	0.016	114	707	6.922	6.110
	Palouse Hopper	0.1151	0.039	91	564	4.904	4.210
	Tucannon	0.1194	0.092	28	174	1.454	===
	Walla Walla	0.1844	0.086	103	639	3.463	4.290
	Yakima Kiona	0.1214	0.141	72	446	3.677	2.450

Application of method at the sub-watershed scale

In this section of the report the various nitrate loading methods used to examine surface and groundwater impacts were applied to several watersheds at a more refined spatial scale than applied previously. The watersheds examined include: the Yakima River, Crab Creek, Nooksack River and Sumas River (Figure 26). Each of these watersheds has well documented surface and ground water quality issues including elevated nitrate concentrations, among other pollutants, primarily associated with nonpoint source activities. The level of nitrate export was examined within each watershed on a hydrologic unit code (HUC) 5th level scale (10 unit digit HUC). This level of resolution provides the ability to more clearly identify areas with elevated loading, and the sources associated with it.

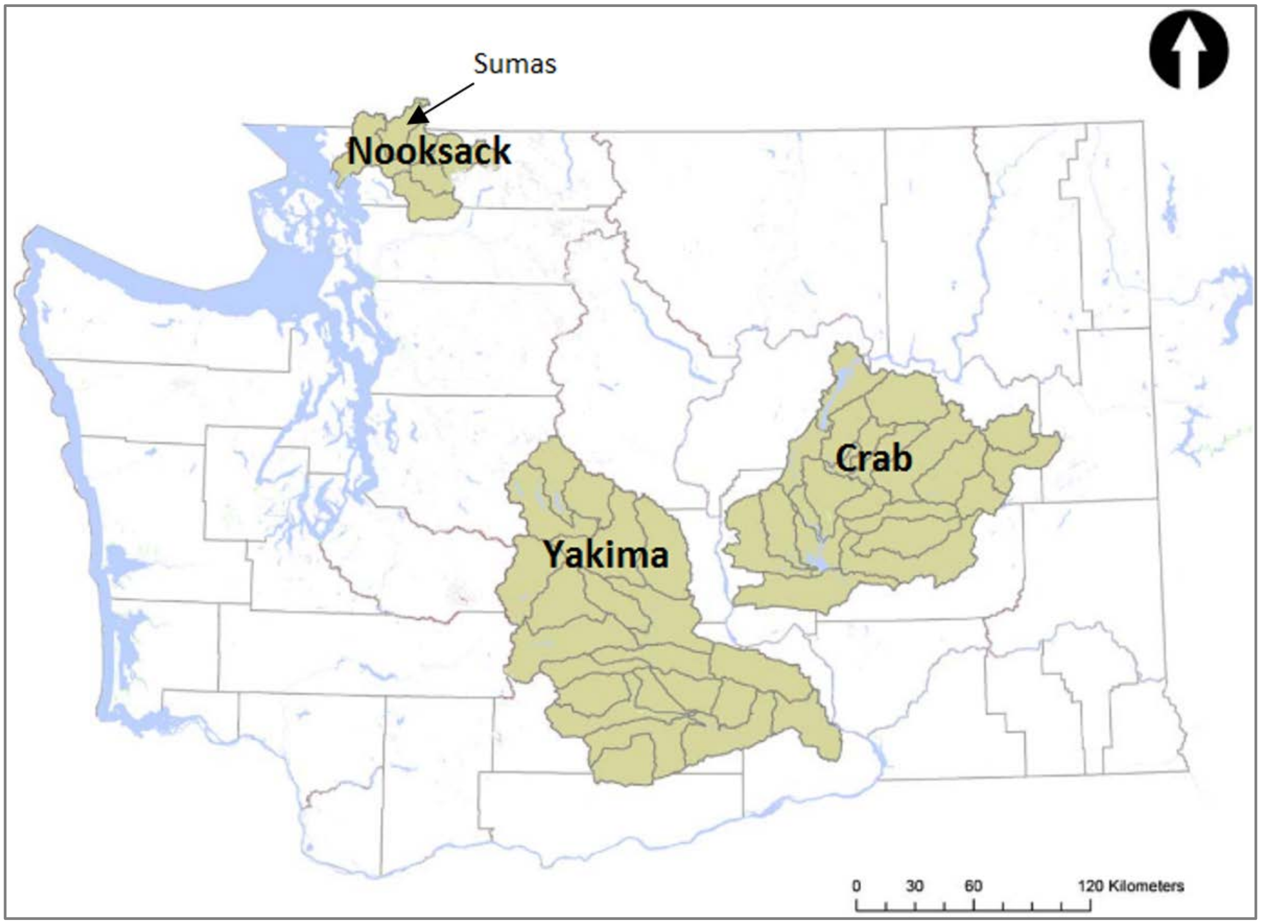

Figure 26. The Nooksack, Yakima, Crab, and Sumas watersheds within Washington State.

The loading estimates are presented from two perspectives based on the potential to impact groundwater or surface water. For groundwater, only the net land-based nitrate loading occurring within each HUC is reported. This perspective excludes the loading attributed to the direct discharge to surface water associated with municipal wastewater, though land-applied discharge was considered. This is the most relevant approach to examining the connection between land surface nitrate loading and impacts to underlying groundwater. Groundwater nitrate levels were determined from the same data sources and methods used previously. Concentration percentiles were generated from wells sampled within each of the HUCs. Only data from samples collected from 30-meters depth or less were considered. Also, at least 15 wells were required to generate percentiles. For this reason, a number of HUCs within each of these watersheds were excluded from the full analysis though loading estimates were still generated.

In terms of impacts to surface water, all sources were considered as well as the application of effective area if a lake or reservoir was in-line with the main flow path. As discussed previously, the effective area only considers the drainage area below the lake/reservoir as providing a significant contribution to loading; the load entering the lake/reservoir is assumed to be largely lost through physical, chemical or biological processes. In addition, instead of reporting the results on a HUC-by-HUC basis, relevant to analyzing groundwater impacts, for surface water, the net nitrate loads are considered cumulatively from headwaters to the most down gradient HUC. Only the Yakima watershed is discussed in this section though the same analysis treatment was determined for Crab Creek, Nooksack River, and the Sumas River. Their case studies are included in Appendix E.

The Yakima watershed

The Yakima watershed, its HUCs and their overall position in the flow network are presented in Figures 27 and 28.

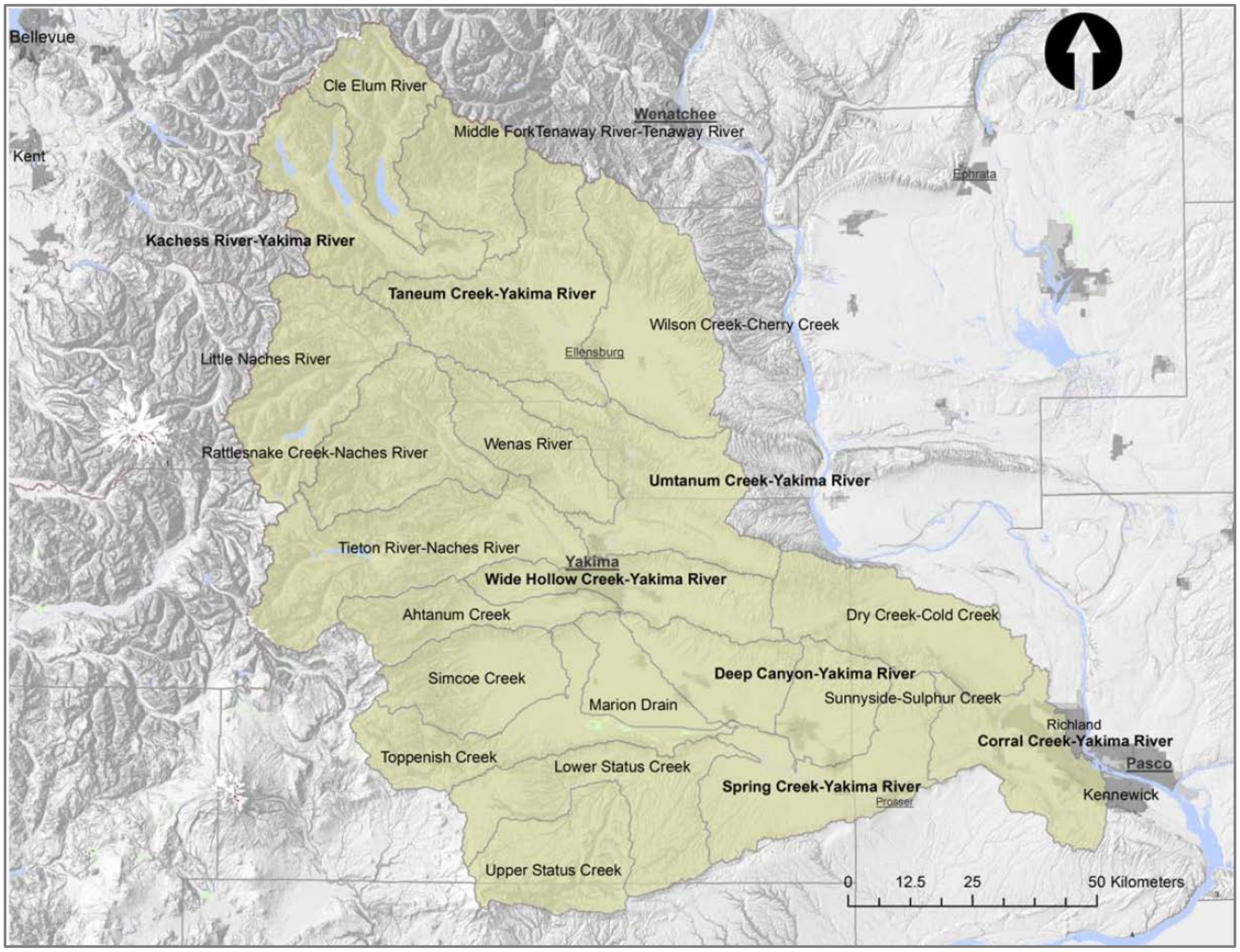

Figure 27. The Yakima River watershed and HUC sub-areas.

Overview of land-use

The Yakima watershed has a wide diversity of land covers from its mountainous and forested upper portions, to transitional shrub lands, and finally to the lower valley, defined here as the portion of the watershed situated below the city of Yakima, an area of major agricultural significance in Washington. From a loading perspective, the higher level of forest lands (which include the lower elevation shrub lands) present in the Cle Elum, Kachess, Little Naches, MF Teanaway, Rattlesnake, Taneum, Tieton, Upper Satus, and Wenas HUCs, all found at a level of representation greater than about 80%, are indicative of a background type nitrate loading condition and, as it will be presented, the groundwater and surface water nitrate levels largely reflect this. Together these HUCs represent about 44% of the Yakima watershed (Table 20). These HUCs can be defined loosely as the upper watershed. A transitional portion of the watershed occurs from the town of Cle Elum (lower portion of Kachess HUC) to greater Ellensburg (Wilson Creek), an area that also includes portions of the Taneum HUC. From Ellensburg, the Yakima flows through a canyon situated in the Umtanum HUC and emerges to the lower valley defined here as the river corridor below Umtanum including: Wide Hollow, Deep Canyon, Spring, and Sunnyside HUCs. From a nitrate loading perspective the lower Yakima valley is where the vast majority of the land uses and activities that contribute to loading occur in the watershed.

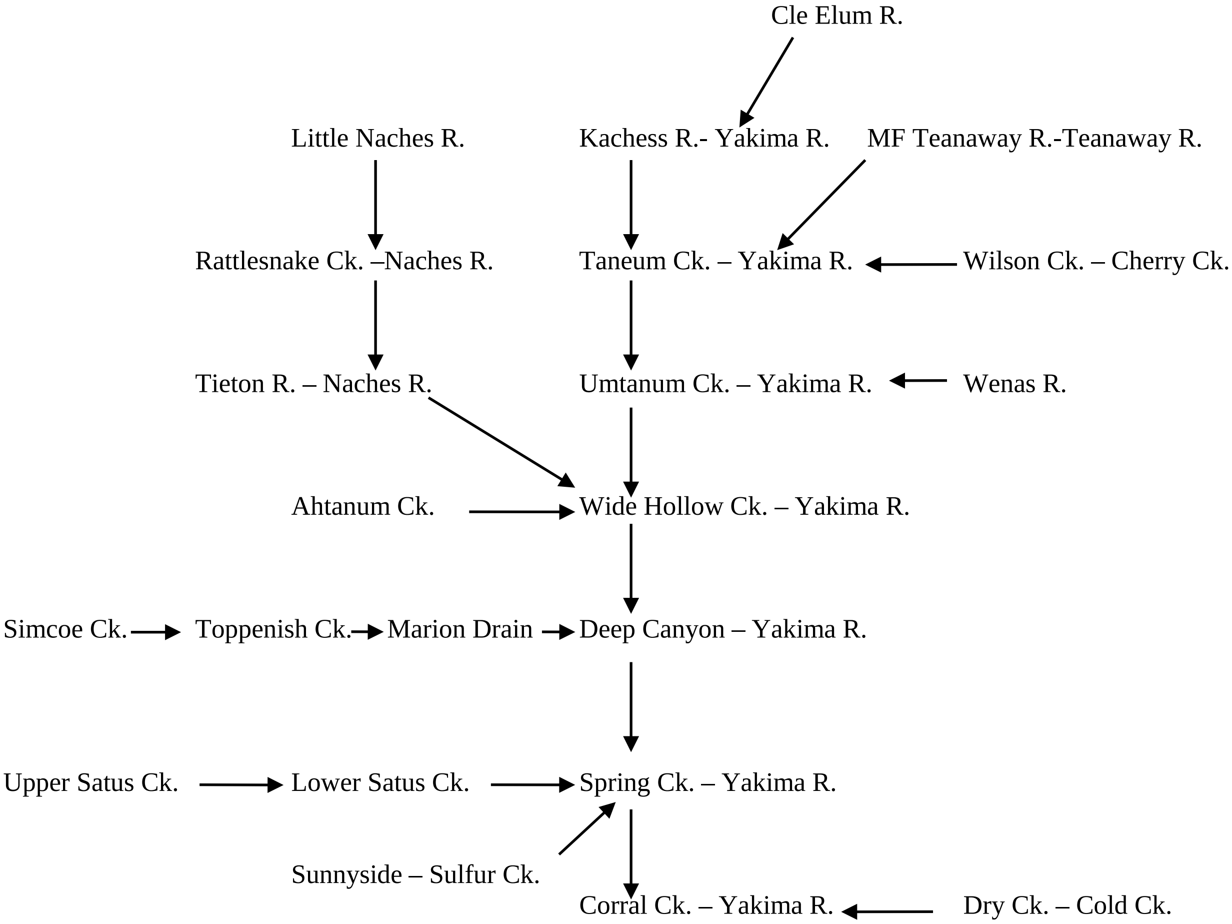

Figure 28. The flow schematic for the Yakima River based on the USGS HUC-10 delineation.

The lower valley receives water for irrigation from reservoir storage situated in the Cle Elum (Cle Elum Lake), Kachess (Keechelus and Kachess Lakes), Little Naches (Bumping Lake) and Tieton (Rimrock Lake) HUCs.

Table 20. The percent representation of NLCD land uses within the Yakima watershed, by hydrologic unit code (HUC).

(HUCs are arranged alphabetically; refer to figure for placement in Yakima flow scheme).

HUC Name HUC (No.)	Drainage Area (km^2)	Open Water	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Ahtanum (1703000301)	442	===	1.8	2.0	70.1	0.2	4.0	8.6	8.2	5.0	===
Cle Elum (1703000101)	573	4.6	0.1	5.1	81.2	0.7	0.1	7.2	===	===	===
Corral (1703000312)	711	0.9	5.7	===	50.6	0.1	13.2	6.0	0.5	22.7	===
Deep Canyon (1703000305)	474	0.7	4.2	0.1	18.4	2.4	17.7	21.8	16.1	18.2	===
Dry Creek (1703000311)	871	===	0.7	0.1	62.5	===	3.8	30.8	0.6	1.5	===
Kachess (1703000103)	808	4.1	1.1	1.1	85.7	1.2	1.9	3.9	0.8	0.1	===
Little Naches (1703000201)	890	1.0	===	2.2	93.1	0.1	===	3.7	===	===	===
Lower Satus (1703000308)	842	0.1	0.1	0.1	68.1	0.3	0.7	30.0	===	0.5	===
MF Teanaway (1703000102)	535	0.2	===	2.0	81.0	0.5	1.5	14.4	===	0.3	===
Marion Drain (1703000304)	334	0.5	6.4	===	5.3	0.3	16.9	6.5	11.7	52.4	===
Rattlesnake (1703000202)	778	0.2	0.1	3.0	87.7	0.2	0.4	8.3	===	===	===
Simcoe (1703000303)	592	===	0.6	0.1	66.2	1.0	9.3	18.4	0.4	3.9	===
Spring (1703000310)	893	0.8	2.4	===	40.4	1.4	11.2	13.3	3.2	27.0	===
Sunnyside (1703000309)	414	0.1	4.2	===	29.1	===	17.5	21.8	1.7	25.7	===
Taneum (1703000105)	1,179	0.3	0.9	0.4	80.3	0.9	7.2	8.0	===	1.9	===
Tieton (1703000203)	1,193	1.3	1.4	2.8	78.4	0.3	2.3	5.2	5.6	2.3	===
Toppenish (1703000306)	713	0.3	0.6	0.1	69.6	0.5	9.9	9.2	2.3	6.0	===
Umtanum (1703000107)	924	0.5	2.2	0.1	68.9	0.2	1.4	23.5	1.8	1.4	===
Upper Satus (1703000307)	617	0.1	===	0.1	87.1	0.4	===	12.2	===	===	===
Wenas (1703000106)	497	0.1	0.6	0.4	77.6	0.3	2.8	13.7	2.1	2.5	===
Wide Hollow (1703000302)	623	0.2	10.0	===	39.0	1.1	6.7	21.4	10.4	11.0	===
Wilson Creek (1703000104)	1,023	0.1	2.7	0.8	63.9	0.5	13.2	8.4	===	10.1	===

Municipal centers within the watershed include Cle Elum (Cle Elum) and Ellensburg (Wilson Creek) situated in the upper and central portions of the watershed, respectively. The lower valley includes the watershed’s urban center, the city of Yakima (Wide Hollow) and its assorted outlying areas. Approximately 30% of the watershed population resides within the Wide Hollow HUC with 77% residing in the lower valley overall (Table 21). Below Yakima, smaller towns are distributed along the river’s flow path ending in the city of Benton and portions of Kennewick and Richland (Corral Creek) at the confluence with the Columbia River. The Corral HUC includes a population of about 62,000, about 17% of the watershed total. Other HUCs with denser populations include Spring (includes the towns of Prosser and Mabton), and Sunnyside (Sunnyside and Grandview) (Table 21). Ellensburg, situated in the Wilson Creek HUC, has a population of about 18,000. Most of these towns have a municipal wastewater treatment plant that has direct or tributary discharge to the Yakima River. About 50% of the municipal WWTP discharge occurs in the Wide Hollow HUC associated with the city of Yakima WWTP with about 80% of the watershed total occurring within the lower valley, consistent with the watershed's population distribution.

The HUCs situated in the western edge of the lower valley are within Yakama Nation lands including: Simcoe, Toppenish, Marion Drain, and upper and lower Satus. In addition, portions of Ahtanum Creek, Deep Canyon, and Spring Creek HUCs are situated within the Yakama lands. Together, Yakama lands comprise about 23% of the watershed and include the towns of Wapato and Toppenish.

Table 21. Yakima HUC nitrate loading attributes including: human, dairy, and beef cattle populations along with the magnitude of municipal wastewater discharge.

HUC Name	Population (No.)	Municipal Surface Discharge (m^3/yr)	Municipal Land Discharge (m^3/yr)	Dairy Cows (No.)	Beef Cows (No.)
Ahtanum	7,700	===	===	===	5,587
Cle Elum	1,212	===	===	===	2,698
Corral	61,557	1,188,391	===	===	4,798
Deep Canyon	19,803	662,818	===	31,618	6,036
Dry Creek	1,183	===	===	===	4,551
Kachess	5,426	1,046,200	149,560	===	3,864
Little Naches	734	===	===	===	9,802
Lower Satus	237	===	===	===	10,512
MF Teanaway	1,569	===	===	===	2,555
Marion Drain	19,091	1,952,532	===	===	4,178
Rattlesnake	783	===	===	===	9,231
Simcoe	2,323	===	===	===	7,586
Spring	25,394	1,172,607	2,003,587	20,379	9,254
Sunnyside	26,567	1,644,004	1,107,076	26,934	4,646
Taneum	6,759	4,531,527	===	414	5,688
Tieton	16,219	331,712	206,490	===	15,160
Toppenish	2,312	===	===	===	9,419
Umtanum	17,280	1,634,821	===	===	7,916
Upper Satus	237	===	===	===	6,582
Wenas	4,376	===	===	===	5,586
Wide Hollow	108,489	14,023,277	===	1,171	8,150
Wilson Creek	21,148	277,336	===	===	4,857
Watershed	**360,401**	**28,465,226**	**3,466,713**	**80,516**	**148,657**

The lower valley is the center of agricultural production in the watershed. The greatest representation of pasture/hay is found for the Sunnyside (18%), Deep Canyon (18%), Marion Drain (17%), and Wilson Creek (13%) (Table 20). Orchard lands are most prominent in Deep Canyon (16% of watershed area), Marion Drain (12%), and Wide Hollow (10%). Small grain is highly represented in the Marion Drain (52% of watershed area), Spring (27%), Sunnyside (26%), and Corral (23%) HUCs. Dairy production is centered in Deep Canyon (39% of watershed cow population), Spring (25%) and Sunnyside (33%) HUCs (Table 21). Beef cattle populations occur at a more equitable distribution throughout the watershed.

Loading to surface and groundwater

Land surface nitrate load / groundwater impacts

The net nitrate loading yields to land surface for each of the Yakima HUCs are presented in Figure 29. Yields exceeding 200 kg/km^2-yr include Spring (221 kg/km^2-yr), Deep Canyon (397 kg/km^2-y), and Sunnyside (415 kg/km^2-y) HUCs, all situated in the lower valley. For each of these HUCs, dairy production is the main contributor of nitrate (Tables 22 and 23). The percent of the net annual load attributed to dairy waste is 71% for Deep Canyon, 66% (Sunnyside) and 44% (Spring).

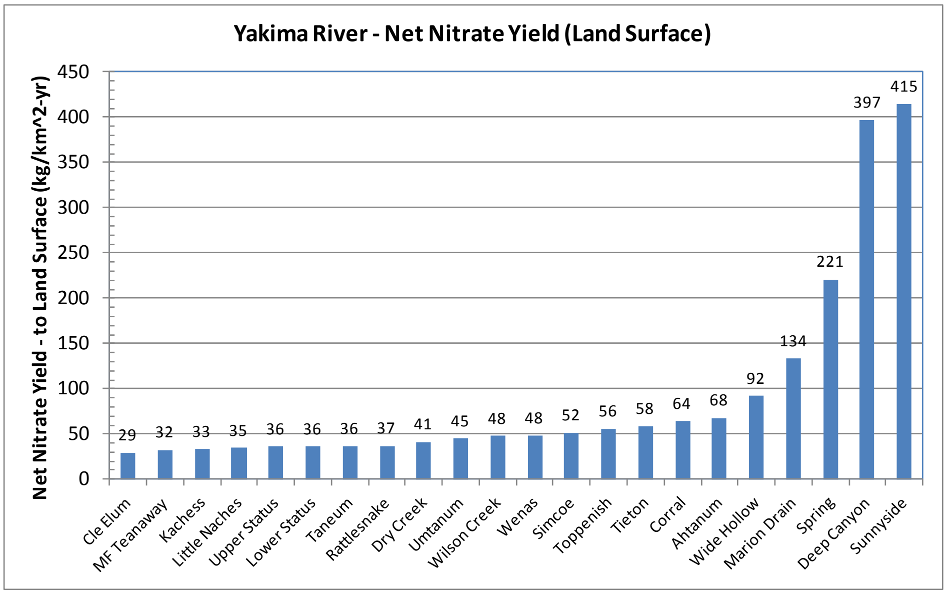

Figure 29. Yakima HUC net land surface nitrate yields.

From Table 23, considering all land-based loading sources within the watershed, dairy production contributes approximately 27% of total annual net land-based load, followed by forest (18%), and beef cows (13%). Excluding sources considered background (forest, shrub lands, and bare rock) then the contributions increase to 34% (dairy), 16% (beef), and 14% (small grain) together accounting for about 64% of the total. Though, importantly, dairies are concentrated within a relatively small section of the watershed, with 98% of the dairy cow population situated within just three HUCs which, together, comprise just 11% of the total area. The dairies are located on the valley floor further compressing their presence to just 4% of the watershed since they are situated in just 30% of the total area within the three HUCs. It is expected that for sources like dairies, where the actual loading is very concentrated, groundwater in proximity to them will be considerably more elevated than the overall HUC average predicted by this analysis.

Table 22. Estimated net land surface nitrate load applied annually within each Yakima HUC.

HUC Name	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Land-Based Municipal Wastewater	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain
Ahtanum	276	222	6,512	17	===	2,079	===	6,034	1,412	1,892	8,700	2,873
Cle Elum	10	1,485	9,780	79	===	327	===	2,914	25	2,064	58	===
Corral	1,266	1	7,560	11	===	===	===	5,182	7,507	2,151	868	21,029
Deep Canyon	601	1	1,830	242	===	4,050	133,585	6,518	6,698	5,170	18,311	11,236
Dry Creek	201	2	11,431	6	===	320	===	4,915	2,620	13,402	1,335	1,711
Kachess	268	383	14,540	198	2,991	===	===	4,173	1,208	1,569	1,477	138
L. Naches	1	895	17,389	17	===	198	===	10,586	===	1,626	===	===
L. Satus	17	3	12,044	58	===	64	===	11,353	467	12,624	===	599
MF Teanaway	6	277	9,090	52	===	424	===	2,760	637	3,851	4	243
Marion Drain	640	===	371	18	===	1,334	===	4,512	4,509	1,085	9,353	22,724
Rattlesnake	28	608	14,318	40	===	212	===	9,770	265	3,215	6	8
Simcoe	105	6	8,225	118	===	627	===	8,193	4,379	5,453	511	2,970
Spring	681	1	7,580	265	40,072	642	86,101	9,995	7,967	5,948	6,896	31,287
Sunnyside	517	===	2,526	3	22,142	1,790	113,795	5,017	5,786	4,507	1,723	13,810
Taneum	319	83	19,884	213	===	===	1,749	6,143	6,781	4,743	===	2,913
Tieton	487	869	19,635	76	4,130	3,326	===	16,372	2,196	3,101	15,939	3,585
Toppenish	140	5	10,422	76	===	624	===	10,172	5,661	3,297	4,003	5,600
Umtanum	625	2	13,373	40	===	1,467	===	8,550	1,058	10,869	3,931	1,631
U. Satus	5	4	11,286	56	===	64	===	7,109	===	3,777	===	===
Wenas	86	21	8,093	29	===	1,182	===	6,033	1,101	3,403	2,449	1,646
Wide Hollow	1,970	1	5,103	143	===	1,855	4,948	8,802	3,333	6,652	15,494	8,894
Wilson Creek	957	69	13,731	108	===	===	===	5,246	10,797	4,296	===	13,481
Watershed	9,208	4,939	224,722	1,867	69,334	20,586	340,178	160,549	74,407	104,695	91,060	146,376

Table 23. Percent representation of the net annual load applied to land surface, by land use, for Yakima HUCs.

HUC Name	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Land-Based Municipal Wastewater	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain
Ahtanum	0.9	0.7	21.7	0.1	===	6.9	===	20.1	4.7	6.3	29.0	9.6
Cle Elum	0.1	8.9	58.4	0.5	===	2.0	===	17.4	0.1	12.3	0.3	===
Corral	2.8	===	16.6	===	===	===	===	11.4	16.5	4.7	1.9	46.1
Deep Canyon	0.3	===	1.0	0.1	===	2.2	71.0	3.5	3.6	2.7	9.7	6.0
Dry Creek	0.6	===	31.8	===	===	0.9	===	13.7	7.3	37.3	3.7	4.8
Kachess	1.0	1.4	53.9	0.7	11.1	===	===	15.5	4.5	5.8	5.5	0.5
Little Naches	===	2.9	56.6	0.1	===	0.6	===	34.5	===	5.3	===	===
Lower Satus	===	===	32.3	0.2	===	0.2	===	30.5	1.3	33.9	===	1.6
MF Teanaway	===	1.6	52.4	0.3	===	2.4	===	15.9	3.7	22.2	===	1.4
Marion Drain	1.4	===	0.8	===	===	3.0	===	10.1	10.1	2.4	21.0	51.0
Rattlesnake	0.1	2.1	49.9	0.1	===	0.7	===	34.8	0.9	11.2	===	===
Simcoe	0.3	===	26.9	0.4	===	2.1	===	26.8	14.3	17.8	1.7	9.7
Spring	0.3	===	3.8	0.1	20.3	0.3	43.6	5.1	4.0	3.0	3.5	15.8
Sunnyside	0.3	===	1.5	===	12.9	1.0	66.3	2.9	3.4	2.6	1.0	8.0
Taneum	0.7	0.2	46.4	0.5	===	===	4.1	14.3	15.8	11.1	===	6.8
Tieton	0.7	1.2	28.2	0.1	5.9	4.8	===	23.5	3.1	4.4	22.9	5.1
Toppenish	0.3	===	26.1	0.2	===	1.6	===	25.4	14.2	8.2	10.0	14.0
Umtanum	1.5	===	37.2	0.1	===	3.5	===	20.6	2.5	26.2	9.5	3.9
Upper Satus	===	===	50.6	0.3	===	0.3	===	31.9	===	16.9	===	===
Wenas	0.4	0.1	33.7	0.1	===	4.9	===	25.1	4.6	14.2	10.2	6.8
Wide Hollow	3.4	===	8.9	0.3	===	3.2	8.7	15.4	5.8	11.6	27.1	15.6
Wilson Creek	2.0	0.1	28.2	0.2	===	===	===	10.8	22.2	8.8	===	27.7
Watershed	**0.7**	**0.4**	**18.0**	**0.1**	**5.6**	**1.6**	**27.3**	**12.9**	**6.0**	**8.4**	**7.3**	**11.7**

HUCs with reduced land-based loading, reflecting more of a background condition, are those with net yields below about 40 kg/km^2-yr including: Cle Elum, MF Teanaway, Kachess, Taneum, Little Naches, Upper and Lower Satus, and Rattlesnake. All are situated up-gradient of the valley floor with a high percentage of the annual load associated with background sources (forest / shrub-land). Together these HUCs comprise about 39% of the total watershed area. The median of the 65th percentile nitrate concentrations (only considering Kachess and Taneum due to the low level of monitoring occurring in the other HUCs) is 0.89 mg/L, close to the expected background concentration for groundwater in eastern Washington.

HUCs with net nitrate yields between approximately 60 to 140 kg/km^2-yr include Toppenish, Tieton, Corral, Ahtanum, Wide Hollow, and Marion Drain. A prominent nitrate source within this group is orchard production averaging about 25% of the annual load. Corral is the exception, with no significant contribution from orchard production. Instead, the major source is small grain production comprising 46% of the annual load, a source also prominent in Marion Drain (51%) and Wilson Creek (28%). The median of the 65th percentile nitrate concentrations among this group is about 3 mg/L (Table 24). The 65th percentile groundwater concentration observed for Tieton and Corral HUCs conform more closely to that expected given the net yield estimated. Tieton and Corral are situated at the upper and lower boundaries of the lower valley, respectively. The other HUCs are all situated in the lower valley and several have lower groundwater nitrate concentrations than expected given their estimated yield including Deep Canyon, Simcoe, and Spring. As discussed previously the reduced impact or the surface loading to groundwater is believed associated with the selective capture of shallow subsurface infiltration by tile drainage prior to its introduction to groundwater.

Table 24. Shallow groundwater nitrate concentrations and associated land-based loading yields, by Yakima HUC.

Drainage Name	Area (km^2)	Sample No.	Groundwater Nitrate Concentration (mg/L)			Land-Based Annual Yield (kg/km^2-yr)
			65th Percentile	75th Percentile	25th Percentile	
Ahtanum	442	22	1.846	2.318	0.358	68
Corral	711	37	3.412	4.667	0.200	64
Deep Canyon	474	80	2.036	3.275	0.594	397
Kachess	808	27	0.395	0.420	0.181	33
Marion Drain	334	305	2.900	3.400	1.400	134
Simcoe	592	47	0.750	0.870	0.255	52
Spring	893	67	2.306	3.200	0.057	221
Sunnyside	414	19	7.969	9.548	1.769	415
Taneum	1,179	20	1.394	1.651	0.290	36
Tieton	1,193	57	3.412	3.630	1.590	58
Toppenish	713	80	1.535	2.050	0.198	56
Wide Hollow	623	81	3.033	3.350	0.640	92
Wilson	1,023	20	0.828	1.424	0.405	48

Loading to surface water

Tables 25 and 26 provide an overview of the net nitrate load to surface water by HUC and cumulatively along the watershed's flow path, respectively. The change in yield between the land-based load and that of surface water is due to the application of effective area, accounting for surface water storage effects, and municipal wastewater discharge. The shaded rows in Table 26 are the Yakima main-stem HUCs. Other rows are organized into primary, secondary, and tertiary tributary HUCs (refer to Figure 28). Focusing on the main-stem at the upper end of the watershed, the Kachess HUC receives the Cle Elum WWTP discharge with Taneum receiving discharge from Ellensburg and Kittitas WWTPs. These inflows, particularly Ellensburg's WWTP, contribute about 15% of the watershed's total WWTP inflows and are a reason for the increase in net yield from 28 to 58 kg/km^2-yr. The largest WWTP inflow is from the Yakima WWTP which alone comprises about 44% of the total wastewater discharged to the Yakima River. The Wide Hollow HUC receives the Yakima WWTP discharge. From the Umtanum to

Wide Hollow, the net nitrate yield increases by 46% from 57 to 83 kg/km^2-yr. A further 8% of the total WWTP inflow is added between Wide Hollow and Deep Canyon associated with the Toppenish, Wapato, Zillah and Granger WWTPs and another 19% between the Deep Canyon and Spring HUCs. Inflows through this section of the watersheds are associated with discharges from the Mabton, Prosser, and Sunnyside WWTPs. In total about 70% of the watershed's total WWTP discharge occurs in the lower valley. Of the sources considered, WWTPs contribute the greatest loading to surface water, accounting for about 31% of the watershed total. While some land infiltration of wastewater does occur, the majority (89%) is discharged to surface water. The other major sources are dairy production (19% of the watershed total) and beef (9%). The beef cattle population has a larger distribution in comparison to the dairy cow population and, therefore, tends to have a lower overall impact to both surface and groundwater.

Table 25. The estimated net annual nitrate loading to surface water and land surface for Yakima HUCs.

HUC Name	Drainage Area (km^2)	Net Nitrate Load and Yield to Land Surface		Net Nitrate Load and Yield to Surface Water*	
		kg/yr	kg/km^2-yr	kg/yr	kg/km^2-yr
Ahtanum	442	30,015	68	29,843	68
Cle Elum	573	16,750	29	7,028	12
Corral	711	45,577	64	62,650	88
Deep Canyon	474	188,243	397	198,226	418
Dry Creek	871	35,947	41	35,750	41
Kachess	808	26,964	33	32,099	40
Little Naches	890	30,714	35	26,029	29
Lower Satus	842	37,230	44	36,421	43
MF Teanaway	535	17,362	32	16,040	30
Marion Drain	334	44,545	134	81,907	246
Rattlesnake	778	28,671	37	27,075	35
Simcoe	592	30,588	52	30,314	51
Spring	893	197,437	221	213,469	239
Sunnyside	414	171,619	415	204,233	493
Taneum	1,179	42,837	36	129,430	110
Tieton	1,193	69,718	58	46,609	39
Toppenish	713	40,003	56	38,014	53
Umtanum	924	41,546	45	69,388	75
Upper Satus	617	22,302	36	21,632	35
Wenas	497	24,043	48	10,066	20
Wide Hollow	623	57,195	92	336,156	540
Wilson Creek	1,023	48,688	48	53,143	52
Watershed	**15,925**	**1,247,994**	**78**	**1,705,516**	**107**

Table 26. The cumulative annual nitrate loading to surface water and land surface by Yakima HUC.

3º Tributary	2º Tributary	1º Tributary	Yakima Main-stem	Net Cumulative Nitrate Load (kg/yr) and yield (kg/km^2-yr)			
				Surface Water		Land Surface	
				Load	Yield	Load	Yield
		Cle Elum 1703000101		7,028	12	16,750	29
			Kachess 1703000103	39,127	28	43,714	32
		MF Teanaway 1703000102		16,040	30	17,362	32
		Wilson Creek 1703000104		53,143	52	48,688	48
			Taneum 1703000105	237,740	58	152,601	37
		Wenas 1703000106		10,066	20	24,043	48
			Umtanum 1703000107	317,193	57	218,190	39
Little Naches 1703000201				26,029	29	30,714	35
	Rattlesnake 1703000202			53,104	32	59,384	36
		Tieton 1703000203		99,712	35	129,102	45
		Ahtanum 1703000301		29,843	68	30,015	68
			Wide Hollow 1703000302	782,899	83	434,502	46
Simcoe 1703000303				30,314	51	30,588	52
	Toppenish 1703000306			68,328	52	70,591	54
		Marion Drain 1703000304		150,235	92	115,136	70
			Deep Canyon 1703000305	1,131,361	98	737,882	64
	Upper Satus 1703000307			21,632	35	22,302	36
		Lower Satus 1703000308		58,653	40	59,532	41
		Sunnyside 1703000309		204,233	493	171,619	415
			Spring 1703000310	1,607,116	112	1,166,469	81
		Dry Creek 1703000311		35,750	41	35,947	41
			Corral 1703000312	1,705,516	107	1,247,994	78

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Appendix A. Figures

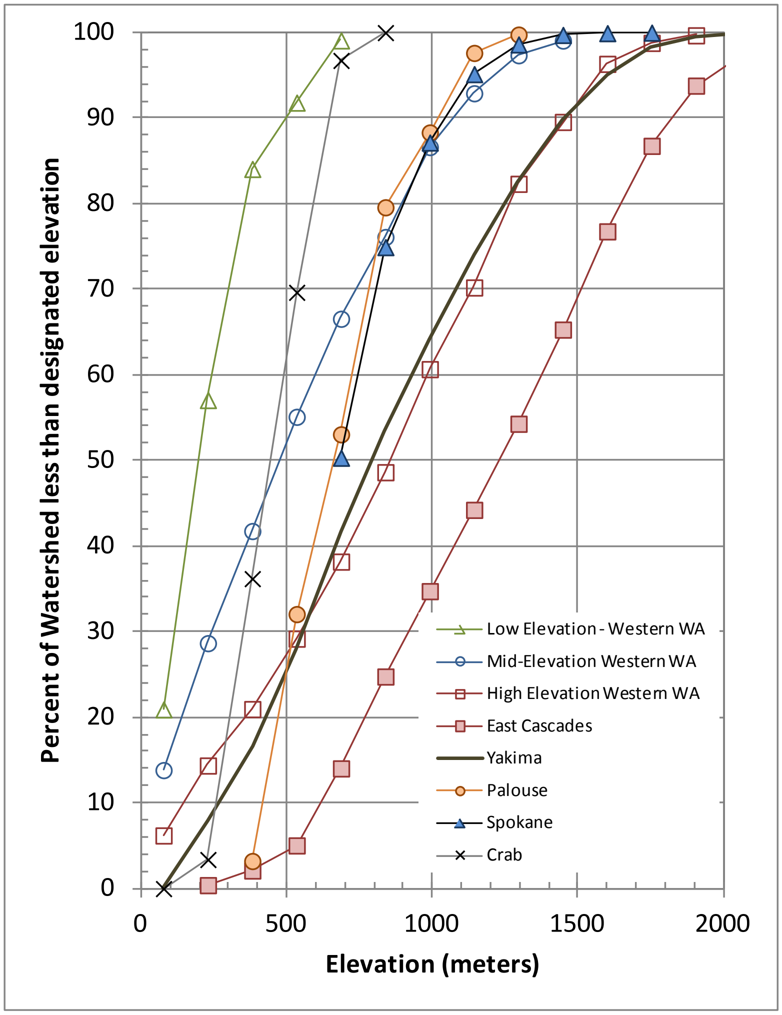


Figure A-1. The cumulative frequency distribution of elevation (meters), by watershed group.

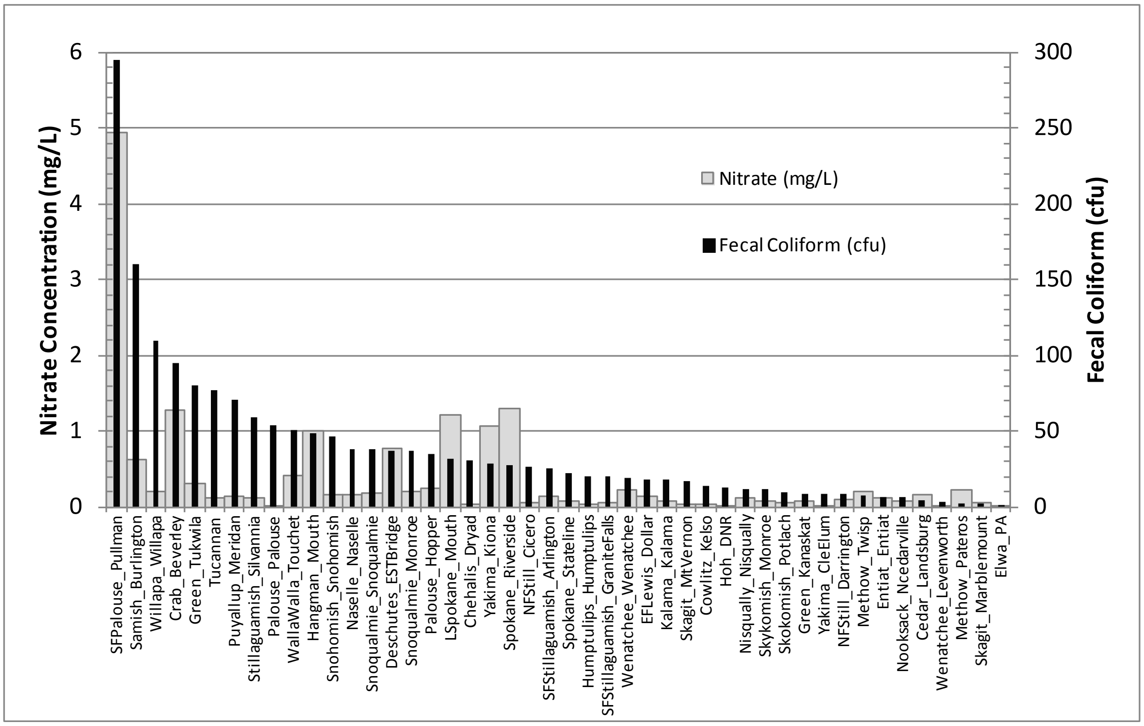


Figure A-2. The relationship between the median September (base-flow) nitrate and fecal coliform levels observed at the monitoring locations.

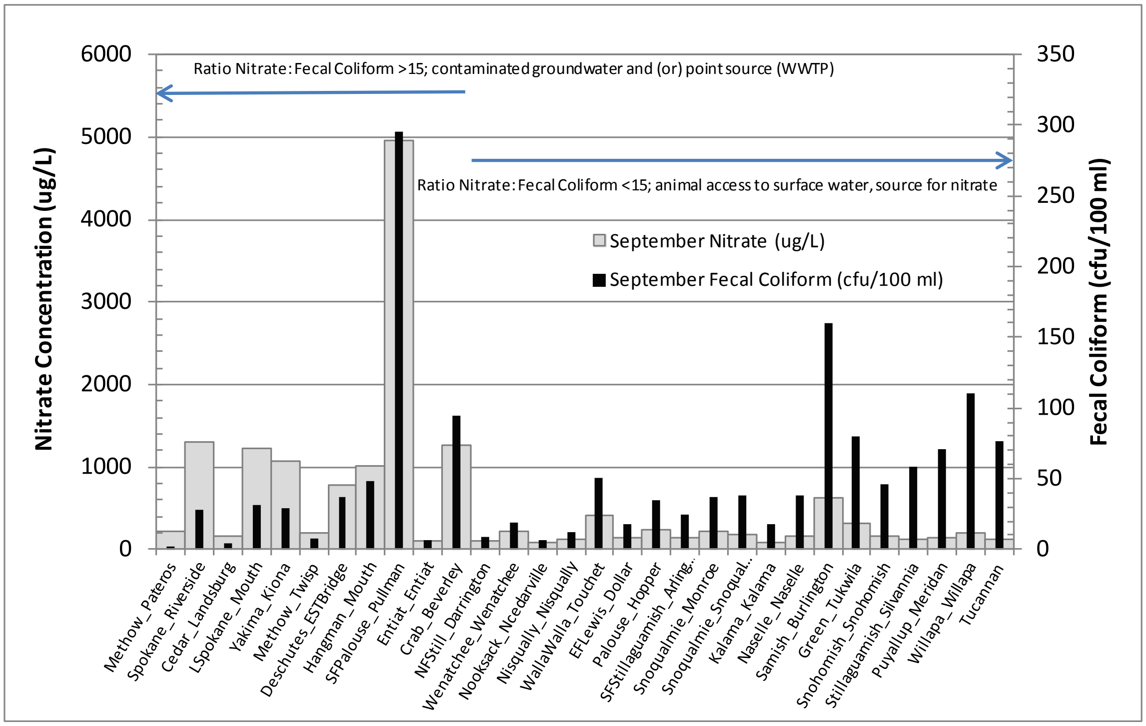


Figure A-3. The relationship between median September (base-flow) nitrate and fecal coliform levels observed at the study monitoring locations for nitrate concentrations greater than 80 ug/L.

Appendix B. Tables

Table B-1. Study monitoring stations, their drainage area, location, and data record period.

Station Name	Drainage Area (km^2)	Elevation (m)	Latitude / Longitude	Data Record No. Years (n)	Location E = East W =West
Cedar @Logan	455	188	47.3913 / 121.9205	85-91, 94-13 (27)	W
Chehalis @Dryad	476	79	46.6309 / 123.2501	85-13 (29)	W
Cowlitz @Kelso	6,048	2	46.1454 / 122.9143	85-13 (29)	W
Crab nr Beverly	13,002	154	46.8313 / 119.8162	85-91,94-13 (27)	E
Deschutes @East Bridge	416	28	47.0118 / 122.9032	85-93,95-13 (28)	W
E.F. Lewis nr Dollar Corner	394	21	45.8146 / 122.5918	85-92, 95-13 (27)	W
Elwha nr Port Angles	751	67	48.0654 / 123.5777	94-13 (20)	W
Entiat nr Entiat	1,065	232	47.6632 / 120.2506	85-91,94-13 (27)	E
Green @Kanaskat	608	236	47.3193 / 121.8935	85-13 (29)	W
Green @Tukwila	1,212	1	47.4654 / 122.2479	91-13 (23)	W
Hangman @mouth	1,776	524	47.6546 / 117.4543	85-91,93,95-13 (27)	E
Hoh @DNR Campground	639	107	47.8098 / 124.2477	94-13 (20)	W
Humptulips nr Humptulips	344	44	47.2298 / 123.9618	85-13 (29)	W
Kalama nr Kalama	524	12	46.0473 / 122.8373	85-92,95-13 (27)	W
Little Spokane nr mouth	1,742	465	47.7829 / 117.5305	85-91,94-13 (27)	E
Methow nr Pateros	4,643	265	48.0746 / 119.9568	85-13 (29)	E
Methow @Twisp	3,261	473	48.3593 / 120.1143	89-91,93,95-13 (23)	E
Naselle nr Naselle	141	23	46.3729 / 123.7468	92,95-13 (20)	W
N.F. Stillaguamish @Ciscero	660	34	48.2673 / 122.0131	85-91,93,95-13 (27)	W
N.F. Stillaguamish nr Darrington	213	133	48.2800 / 121.7024	93, 95-13 (20)	W
Nisqually @Nisqually	1,828	6	47.0620 / 122.6964	85-13 (29)	W
Nooksack @No. Cedarville	1,520	43	48.8416 / 122.2936	85-91,93,95-13 (27)	W
Palouse @Hopper	8,818	323	46.7586 / 118.1480	85-13 (29)	E
Palouse @Palouse	888	637	46.9091 / 117.0768	92, 94-13 (22)	E
Puyallup @Meridian St.	2,473	9	47.2026 / 122.2937	85-13 (29)	W
Samish nr Burlington	223	12	48.5458 / 122.3382	85-91,93,95-13 (27)	W
S.F. Palouse @Pullman	332	707	46.7324 / 117.1810	85-92,95-13 (27)	E
S.F. Stillaguamish @Arlington	648	17	48.2007 / 122.1190	85-91,93,95-13 (27)	W
S.F. Stillaguamish nr Granite Falls	309	88	48.1028 / 121.9532	93, 95-13 (20)	W
Skagit @Marblemount	3,263	110	48.5268 / 121.4290	85-13 (29)	W
Skagit nr Mount Vernon	8,011	4	48.4451 / 122.3352	85-13 (29)	W
Skokomish nr Potlash	592	18	47.3098 / 123.1771	85-13 (29)	W
Skykomish @Monroe	1,982	13	47.8521 / 121.9592	85-93,95-13 (28)	W
Snohomish @Snohomish	4,419	2	47.9106 / 122.0988	85-13 (29)	W
Snoqualmie nr Monroe	1,780	5	47.8037 / 122.0028	92-93,95-13 (21)	W
Snoqualmie @Snoqualmie	949	122	47.5269 / 121.8121	85-92,85-13 (27)	W
Spokane @Riverside State Park	12,976	500	47.6966 / 117.4977	85-13 (29)	E
Spokane @Stateline Bridge	10,023	603	47.6985 / 117.0446	91-13 (23)	E
Stillaguamish nr Silvannia	1,454	11	48.1969 / 122.2101	85-13 (29)	W
Tucannon @Powers	1,290	183	46.5376 / 118.1555	85-92,95-13 (27)	E
Walla Walla nr Touchet	4,423	113	46.0376 / 118.7664	85-13 (29)	E
Wenatchee nr Leavenworth	1,718	507	47.6762 / 120.7340	85-13 (29)	E
Wenatchee @Wenatchee	3,434	189	47.4588 / 120.3365	85-13 (29)	E
Willapa nr Willapa	339	15	46.6501 / 123.6535	85-92,95-13 (27)	W
Yakima nr Cle Elum	643	616	47.1857 / 121.0445	90-92,95-13 (22)	E
Yakima @Kiona	15,314	140	46.2529 / 119.4753	85-13 (29)	E
Yakima @Nob Hill	8,424	300	46.5815 / 120.4617	95-13 (19)	E

Table B-2. NCLD land use classification groups and corresponding descriptions.

Land Use Group	Code - Land Use & Description
Water	11- Open Water Areas of open water, generally with less than 25 percent or greater cover of water (per pixel).
	12- Perennial Snow / Ice All areas characterized by year-long cover of ice and/or snow.
Developed - areas characterized by high percentage (approximately 30% or greater) of constructed materials (e.g. asphalt, concrete, buildings, etc).	21- Low Intensity Residential Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.
	22- High Intensity Residential Includes heavily built up urban centers where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80-100 percent of the cover.
	23- Commercial/Industrial/Transportation Includes infrastructure (e.g. roads, railroads, etc.) and all highways and all developed areas not classified as High Intensity Residential.
Barren - Areas characterized by bare rock, gravel, sad, silt, clay, or other earthen material, with little or no "green" vegetation present, regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the "green" vegetated categories; lichen cover may be extensive.	31- Bare Rock/Sand/Clay Perennially barren areas of bedrock, desert, pavement, scarps, talus, slides, volcanic material, glacial debris, and other accumulations of earthen material.
	32- Quarries/Strip Mines/Gravel Pits Areas of extractive mining activities with significant surface expression
	33- Transitional Areas of sparse vegetative cover (less than 25 percent that are dynamically changing from one land cover to another, often because of land use activities. Examples include forest clear-cuts, a transition phase between forest and agricultural land, the temporary clearing of vegetation, and changes due to natural causes (e.g. fire, flood, etc.)
Vegetated – Natural Forested Upland Areas characterized by tree cover (natural or Semi-natural woody vegetation, generally greater than 6 meters tall); Tree canopy accounts for 25-100 percent of the cover.	41- Deciduous Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously in response to seasonal change.
	42- Evergreen Areas characterized by trees where 75 percent or more of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43- Mixed Forest Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.
Shrub-land - Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall with individuals or clumps not touching to interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included.	51- Shrub-land Areas dominated by shrubs; shrub canopy accounts for 25-100 percent of the cover. Shrub cover is generally greater than 25 percent when tree cover is less than 25 percent. Shrub cover may be less than 25 percent in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25 percent and shrubs cover exceeds the cover of the other life forms.
Non-Natural Woody - Areas dominated by non-natural woody vegetation; non-natural woody vegetative canopy accounts for 25-100 percent of the cover. The non-natural woody classification is subject to the availability of sufficient ancillary data to differentiate non-natural woody vegetation, from natural woody vegetation.	61- Orchards/Vineyards Orchards, vineyards, and other areas planted or maintained for the production of fruits, nuts, berries, or ornamentals.

Land Use Group	Code - Land Use & Description
Herbaceous Planted/Cultivated - Upland areas characterized by natural or semi- natural herbaceous vegetation; herbaceous vegetation accounts for 75-100 percent of the cover.	71- Grasslands/ herbaceous Areas dominated by upland grasses and forbs. In rare cases, herbaceous cover is less than 25 percent, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing.
Planted Cultivated - Areas characterized by herbaceous vegetation that has been planted, or is intensively managed, for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Herbaceous vegetation accounts for 75-100 percent of the cover.	81- Pasture/Hay Areas of grasses, legumes, or grass-legume mixtures, planted for livestock grazing, or the production of seed or hay crops.
	82- Row Crops Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.
	83- Small Grains Areas used for the production of graminoid crops such as wheat, barley, oats, and rice.
	84- Fallow Areas used for the production of crops that are temporarily barren or with sparse vegetative cover as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage.
	85- Urban Recreational Grasses Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses.
Wetlands - Areas where the soil or substrate is periodically saturated with, or covered with water as defined by Cowardin et al.	91- Woody Wetlands Areas where forest or shrub-land vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with, or covered with water.
	92- Emergent Herbaceous Wetlands Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with, or covered with water.

Table B-3. The monitoring stations, their grouping and associated watershed metrics.
(Study watersheds are ordered alphabetically.)

Monitoring Site	Flow Group	Area (km^2)	Annual Precipitation (m)	Annual Flow Yield (m^3/ m^2-yr)	Annual Nitrate Yield (kg/ km^2-yr)	Annual Average Nitrate Concentration (flow-weighted) (ug/L)	Base-Flow Nitrate Concentration (flow-weighted) (ug/L)
Cedar @Logan	Storage	455	2.12	1.131	192	170	171
Chehalis @Dryad	Low Elevation	476	2.10	1.031	484	487	34
Cowlitz @Kelso	Storage	6,048	1.84	1.124	204	181	39
Crab nr Beverly	Crab	13,002	0.19	0.016	29	1,869	1,265
Deschutes @East Bridge	Groundwater	416	1.33	0.675	424	630	771
E.F. Lewis nr Dollar Corner	Low Elevation	394	2.07	1.253	456	364	121
Elwha nr Port Angles	Storage	751	2.66	1.465	25	17	10
Entiat nr Entiat	E. Cascade	1,065	1.09	0.355	16	45	85
Green @Kanaskat	Storage	608	2.10	1.016	130	128	68
Green @Tukwila	Storage	1,212	1.65	0.804	330	411	308
Hangman @mouth	Palouse	1,776	0.46	0.068	263	3,867	927
Hoh @DNR Campground	High Elevation	639	3.36	2.846	216	76	10
Humptulips nr Humptulips	Low Elevation	344	3.19	2.529	361	143	28
Kalama nr Kalama	Mid Elevation	524	2.17	1.274	425	333	69
Little Spokane nr mouth	Groundwater	1,742	0.54	0.269	287	1,066	1,197
Methow @Pateros	E. Cascade	4,643	0.75	0.243	19	80	55
Methow @Twisp	E. Cascade	3,261	0.81	0.333	23	69	156
Naselle nr Naselle	Low Elevation	141	2.67	2.044	995	488	125
NF Stillaguamish @Ciscero	Mid Elevation	660	2.52	2.015	394	195	58
NF Stillaguamish @Darrington	Mid Elevation	213	2.63	1.664	239	144	91
Nisqually @Nisqually	Storage	1,828	1.56	0.857	217	253	118
Nooksack @Cedar	High Elevation	1,520	2.13	1.762	305	173	69
Palouse @Hopper	Palouse	8,818	0.34	0.039	110	2,814	157
Palouse @Palouse	Palouse	888	0.51	0.240	126	525	10
Puyallup @Meridian St.	Storage	2,473	1.73	1.011	225	223	108
Samish nr Burlington	Groundwater	223	1.17	0.825	611	739	636
S.F. Palouse @Pullman	Palouse	332	0.43	0.073	418	5,700	4,142
SF Stillaguamish @Arlington	Mid Elevation	648	2.60	1.703	377	221	139
SF Stillaguamish @Granite Falls	High Elevation	309	3.03	2.489	252	101	43
Skagit @Marblemount	Storage	3,263	2.23	1.600	100	63	52
Skagit @Mount Vernon	High Elevation	8,011	2.44	1.630	169	104	42
Skokomish @Potlash	Storage	592	3.18	1.297	155	70	49
Skykomish @Monroe	High Elevation	1,982	2.76	2.169	292	134	63
Snohomish @Snohomish	High Elevation	4,419	2.32	1.604	400	249	148
Snoqualmie @Monroe	High Elevation	1,780	2.26	1.592	473	297	193
Snoqualmie @Snoqualmie	High Elevation	949	2.85	1.884	354	188	170
Spokane @Riverside	Spokane	12,976	0.49	0.378	163	432	1,228
Spokane @Stateline	Spokane	10,023	0.77	0.460	22	48	86
Stillaguamish @Silvannia	Mid Elevation	1,454	2.48	1.788	455	254	105
Tucannon @Powers	Palouse	1,290	0.47	0.092	22	243	122
Walla Walla nr Touchet	Palouse	4,423	0.41	0.086	60	702	460
Wenatchee @Leavenworth	Storage	1,718	1.86	0.979	40	41	10
Wenatchee @Wenatchee	E. Cascade	3,434	1.47	0.681	55	80	168
Willapa @Willapa	Low Elevation	339	2.03	1.170	894	763	179
Yakima @Cle Elum	Storage	643	1.77	0.802	16	19	10
Yakima @Kiona	Yakima	15,314	0.64	0.141	117	826	1,039
Yakima @Nob Hill	Yakima	8,424	0.91	0.336	43	128	106

Table B-4. Drainage area and elevation characteristics for the study monitoring stations.

Monitoring Station	Drainage Area (km^2)	Station Elevation (m)	% of drainage area abv. 1000 m	% of drainage area 500- 1000 m
Cedar @Logan	455	188	16.6	31.1
Chehalis @Dryad	476	79	0.0	8.3
Cowlitz @Kelso	6,048	2	29.3	25.1
Crab nr Beverly	13,002	154	0.0	30.3
Deschutes @East Bridge	416	28	0.2	13.0
E.F. Lewis nr Dollar Corner	394	21	3.0	29.3
Elwha nr Port Angles	751	67	54.2	31.4
Entiat nr Entiat	1,065	232	65.3	28.0
Green @Kanaskat	608	236	27.0	52.3
Green @Tukwila	1,212	1	13.4	28.1
Hangman @mouth	1,776	524	2.6	95.8
Hoh @DNR Campground	639	107	27.6	27.5
Humptulips nr Humptulips	344	44	1.2	14.6
Kalama nr Kalama	524	12	4.8	30.5
Little Spokane nr mouth	1,742	465	3.4	79.6
Methow nr Pateros	4,643	265	72.0	23.0
Methow @Twisp	3,261	473	79.9	17.5
Naselle nr Naselle	141	23	0.0	1.7
N.F. Stillaguamish @Ciscero	660	34	15.6	39.6
N.F. Stillaguamish nr Darrington	213	133	17.3	43.9
Nisqually @Nisqually	1,828	6	13.3	25.1
Nooksack @No. Cedarville	1,520	43	35.7	31.2
Palouse @Hopper	8,818	323	1.3	66.6
Palouse @Palouse	888	637	11.7	88.3
Puyallup @Meridian St.	2,473	9	39.3	24.2
Samish nr Burlington	223	12	1.2	10.5
S.F. Palouse @Pullman	332	707	3.4	96.6
S.F. Stillaguamish @Arlington	648	17	14.2	34.2
S.F. Stillaguamish nr Granite Falls	309	88	21.9	39.6
Skagit @Marblemount	3,263	110	69.6	20.2
Skagit nr Mount Vernon	8,011	4	53.4	23.1
Skokomish nr Potlash	592	18	15.6	29.3
Skykomish @Monroe	1,982	13	42.0	28.9
Snohomish @Snohomish	4,419	2	27.9	23.0
Snoqualmie nr Monroe	1,780	5	22.3	24.0
Snoqualmie @Snoqualmie	949	122	38.1	32.9
Spokane @Riverside State Park	12,975	500	6.2	90.4
Stillaguamish nr Silvannia	1,454	11	13.3	33.7
Tucannon @Powers	1,290	183	27.1	33.9
Walla Walla nr Touchet	4,423	113	15.4	23.5
Wenatchee nr Leavenworth	1,718	507	64.8	30.3
Wenatchee @Wenatchee	3,434	189	56.7	32.1
Willapa nr Willapa	339	15	0.0	2.2
Yakima nr Cle Elum	643	616	50.4	49.6
Yakima @Kiona	15,314	140	30.6	34.6

Table B-5. Monitoring station median monthly nitrate concentrations (mg/L).

Monitoring Station	Monthly Median Nitrate Concentration (mg/L)											
	1	2	3	4	5	6	7	8	9	10	11	12
Cedar @Logan	0.188	0.196	0.180	0.169	0.148	0.131	0.159	0.173	0.169	0.151	0.160	0.180
Chehalis @Dryad	0.560	0.537	0.429	0.271	0.160	0.120	0.078	0.034	0.034	0.224	0.659	0.595
Cowlitz @Kelso	0.260	0.255	0.245	0.171	0.089	0.072	0.044	0.040	0.039	0.050	0.253	0.243
Crab nr Beverley	2.970	2.920	2.890	1.700	1.300	1.290	1.360	1.260	1.270	1.570	2.300	2.800
Deschutes @East Bridge	0.642	0.705	0.620	0.550	0.527	0.653	0.750	0.767	0.777	0.609	0.580	0.630
E. F. Lewis nr Dollar Corner	0.446	0.367	0.332	0.224	0.170	0.158	0.142	0.105	0.140	0.259	0.463	0.482
Elwha nr Port Angles	0.037	0.023	0.011	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.022	0.027
Entiat nr Entiat	0.120	0.121	0.132	0.040	0.017	0.020	0.026	0.069	0.111	0.141	0.111	0.132
Green @Kanaskat	0.192	0.166	0.129	0.076	0.029	0.045	0.060	0.069	0.067	0.094	0.174	0.209
Green @Tukwila	0.576	0.486	0.410	0.321	0.237	0.269	0.329	0.310	0.307	0.333	0.369	0.531
Hangman @Mouth	4.420	5.210	5.090	2.570	0.723	0.630	0.563	0.831	1.010	0.770	0.611	1.720
Hoh @DNR Campground	0.106	0.083	0.056	0.062	0.017	0.013	0.010	0.010	0.011	0.096	0.134	0.125
Humptulips nr Humptulips	0.160	0.146	0.109	0.083	0.027	0.038	0.030	0.025	0.030	0.174	0.209	0.192
Kalama nr Kalama	0.482	0.369	0.375	0.236	0.119	0.091	0.061	0.051	0.083	0.183	0.460	0.520
Little Spokane nr Mouth	1.250	1.180	1.050	0.750	0.843	0.936	1.110	1.175	1.220	1.230	1.250	1.240
Methow nr Pateros	0.230	0.212	0.154	0.120	0.040	0.033	0.061	0.132	0.216	0.225	0.202	0.232
Methow @Twisp	0.169	0.144	0.126	0.119	0.050	0.033	0.052	0.130	0.204	0.190	0.140	0.157
Naselle nr Naselle	0.527	0.489	0.464	0.384	0.286	0.202	0.157	0.102	0.154	0.479	0.572	0.564
N.F. Stillaguamish @Ciscero	0.255	0.235	0.190	0.138	0.086	0.067	0.053	0.052	0.065	0.211	0.294	0.283
N.F. Stillaguamish nr Darrington	0.200	0.170	0.145	0.106	0.067	0.057	0.069	0.077	0.107	0.147	0.205	0.181
Nisqually @Nisqually	0.377	0.379	0.333	0.250	0.180	0.127	0.114	0.116	0.120	0.125	0.246	0.290
Nooksack @No. Cedarville	0.293	0.276	0.243	0.168	0.087	0.070	0.049	0.060	0.082	0.162	0.248	0.274
Palouse @Hopper	3.665	4.130	3.940	2.080	1.235	0.960	0.537	0.061	0.236	0.370	1.440	1.950
Palouse @Palouse	0.740	1.022	0.831	0.194	0.034	0.017	0.010	0.010	0.010	0.010	0.010	0.163
Puyallup @Meridian St.	0.450	0.333	0.283	0.192	0.094	0.082	0.086	0.088	0.141	0.151	0.273	0.349
Samish nr Burlington	0.895	0.838	0.720	0.624	0.555	0.607	0.631	0.652	0.618	0.619	0.691	0.770
S. F. Palouse @Pullman	5.870	7.515	6.440	4.760	3.300	2.840	2.670	2.930	4.950	5.570	4.610	5.200
S. F. Stillaguamish @Arlington	0.318	0.314	0.239	0.182	0.100	0.092	0.099	0.133	0.145	0.204	0.286	0.304
S. F. Stillaguamish nr Granite Falls	0.131	0.130	0.126	0.090	0.063	0.048	0.028	0.022	0.063	0.125	0.150	0.146
Skagit @Marblemount	0.070	0.063	0.065	0.069	0.072	0.050	0.047	0.048	0.057	0.061	0.069	0.071
Skagit nr Mount Vernon	0.152	0.137	0.130	0.113	0.079	0.060	0.040	0.040	0.045	0.086	0.133	0.170
Skokomish nr Potlach	0.079	0.071	0.056	0.044	0.031	0.027	0.033	0.038	0.062	0.082	0.103	0.099
Skykomish @Monroe	0.222	0.197	0.161	0.116	0.065	0.045	0.039	0.049	0.078	0.136	0.198	0.212
Snohomish @Snohomish	0.410	0.338	0.304	0.211	0.110	0.101	0.105	0.126	0.168	0.207	0.294	0.401
Snoqualmie nr Monroe	0.459	0.363	0.328	0.258	0.153	0.143	0.146	0.177	0.209	0.244	0.341	0.465
Snoqualmie @Snoqualmie	0.268	0.253	0.214	0.171	0.101	0.093	0.116	0.159	0.183	0.195	0.244	0.260
Spokane @Riverside St. Park	0.635	0.689	0.596	0.267	0.180	0.253	0.691	1.150	1.295	0.727	0.560	0.517
Spokane @Stateline Bridge	0.061	0.060	0.070	0.062	0.032	0.013	0.043	0.093	0.077	0.046	0.041	0.050
Stillaguamish nr Silvannia	0.331	0.344	0.251	0.203	0.110	0.120	0.090	0.091	0.119	0.235	0.313	0.376
Tucannan @Powers	0.414	0.554	0.448	0.197	0.109	0.102	0.140	0.118	0.126	0.145	0.170	0.318
Walla Walla nr Touchet	0.851	1.015	0.780	0.553	0.415	0.430	0.502	0.540	0.420	0.633	0.530	0.827
Wenatchee nr Leavenworth	0.054	0.053	0.037	0.046	0.060	0.044	0.017	0.010	0.010	0.010	0.017	0.052
Wenatchee @Wenatchee	0.135	0.135	0.131	0.030	0.065	0.055	0.064	0.137	0.224	0.202	0.094	0.139
Willapa nr Willapa	0.866	0.800	0.697	0.538	0.320	0.270	0.192	0.159	0.196	0.392	0.944	0.935
Yakima nr Cle Elum	0.049	0.047	0.025	0.014	0.010	0.010	0.012	0.010	0.010	0.010	0.010	0.040
Yakima @Kiona	1.075	0.920	0.669	0.399	0.470	0.590	0.880	0.998	1.070	1.220	1.240	1.140
Yakima @Nob Hill	0.211	0.244	0.143	0.054	0.092	0.092	0.130	0.114	0.097	0.159	0.195	0.204

Table B-6. Monitoring station median monthly ammonia concentrations (mg/L).

Monitoring Station	Monthly Median Ammonia Concentration (mg/L)											
	1	2	3	4	5	6	7	8	9	10	11	12
Cedar @Logan	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Chehalis @Dryad	0.010	0.010	0.010	0.010	0.010	0.013	0.013	0.010	0.010	0.010	0.010	0.010
Cowlitz @Kelso	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Crab nr Beverley	0.031	0.019	0.010	0.010	0.020	0.011	0.017	0.012	0.010	0.010	0.010	0.022
Deschutes @East Bridge	0.013	0.010	0.010	0.010	0.010	0.011	0.013	0.010	0.010	0.010	0.010	0.011
E. F. Lewis nr Dollar Corner	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Elwha nr Port Angles	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Entiat nr Entiat	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Green @Kanaskat	0.010	0.010	0.010	0.010	0.010	0.010	0.011	0.010	0.010	0.010	0.010	0.010
Green @Tukwila	0.020	0.015	0.019	0.013	0.016	0.017	0.044	0.036	0.040	0.025	0.014	0.026
Hangman @Mouth	0.047	0.045	0.026	0.010	0.018	0.016	0.020	0.020	0.011	0.010	0.010	0.020
Hoh @DNR Campground	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Humptulips nr Humptulips	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Kalama nr Kalama	0.010	0.010	0.010	0.010	0.010	0.010	0.011	0.010	0.020	0.010	0.010	0.010
Little Spokane nr Mouth	0.020	0.010	0.015	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Methow nr Pateros	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Methow @Twisp	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Naselle nr Naselle	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
N.F. Stillaguamish @Ciscero	0.013	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.014
N.F. Stillaguamish nr Darrington	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Nisqually @Nisqually	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.012
Nooksack @No. Cedarville	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Palouse @Hopper	0.034	0.045	0.030	0.010	0.020	0.025	0.027	0.013	0.020	0.018	0.012	0.026
Palouse @Palouse	0.028	0.018	0.016	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.10	0.013
Puyallup @Meridian St.	0.030	0.023	0.021	0.019	0.012	0.014	0.020	0.013	0.020	0.017	0.020	0.030
Samish nr Burlington	0.013	0.010	0.010	0.012	0.020	0.010	0.010	0.010	0.011	0.014	0.020	0.022
S. F. Palouse @Pullman	0.137	0.090	0.073	0.054	0.054	0.041	0.040	0.030	0.021	0.020	0.065	0.110
S. F. Stillaguamish @Arlington	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.018	0.010
S. F. Stillaguamish nr Granite Falls	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.011
Skagit @Marblemount	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Skagit nr Mount Vernon	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Skokomish nr Potlach	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.017
Skykomish @Monroe	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Snohomish @Snohomish	0.020	0.013	0.014	0.010	0.010	0.010	0.010	0.010	0.012	0.012	0.017	0.020
Snoqualmie nr Monroe	0.021	0.011	0.015	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Snoqualmie @Snoqualmie	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Spokane @Riverside St. Park	0.056	0.015	0.016	0.012	0.014	0.014	0.014	0.012	0.010	0.010	0.014	0.017
Spokane @Stateline Bridge	0.018	0.011	0.010	0.010	0.010	0.010	0.013	0.014	0.010	0.010	0.010	0.010
Stillaguamish nr Silvannia	0.012	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.016	0.017
Tucannan @Powers	0.010	0.010	0.010	0.010	0.010	0.010	0.011	0.010	0.010	0.010	0.010	0.010
Walla Walla nr Touchet	0.032	0.025	0.020	0.014	0.019	0.020	0.027	0.021	0.018	0.010	0.010	0.027
Wenatchee nr Leavenworth	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Wenatchee @Wenatchee	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Willapa nr Willapa	0.010	0.010	0.010	0.010	0.010	0.018	0.020	0.020	0.020	0.010	0.010	0.010
Yakima nr Cle Elum	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Yakima @Kiona	0.036	0.021	0.020	0.010	0.019	0.016	0.020	0.012	0.010	0.010	0.017	0.030
Yakima @Nob Hill	0.012	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010

Table B-7. Monitoring station median monthly flow levels (m^3/s).

Monitoring Station	Median monthly flow (cubic meters per second)											
	1	2	3	4	5	6	7	8	9	10	11	12
Cedar @Logan	28.9	14.6	21.9	18.9	15.2	15.6	10.8	8.9	8.4	12.0	14.5	25.6
Chehalis @Dryad	28.2	27.2	25.1	14.9	7.4	3.8	2.0	1.4	1.6	7.4	31.4	35.7
Cowlitz @Kelso	311.4	282.8	274.6	230.5	207.2	164.2	121.2	94.7	103.5	151.0	271.2	366.6
Crab nr Beverley	5.3	5.2	4.5	6.5	6.9	6.4	6.1	7.0	8.5	9.1	6.0	5.7
Deschutes @East Bridge	16.1	14.0	15.8	10.1	6.7	4.4	2.9	2.8	2.2	3.8	14.2	13.4
E. F. Lewis nr Dollar Corner	27.2	23.3	27.1	18.2	10.2	8.0	2.7	1.7	1.5	5.5	31.1	30.7
Elwha nr Port Angles	46.7	33.7	38.8	35.1	53.2	49.3	29.4	15.3	10.7	19.1	41.1	45.0
Entiat nr Entiat	3.9	4.3	5.7	10.9	26.6	52.4	18.8	5.4	3.3	2.9	4.4	4.7
Green @Kanaskat	35.2	24.3	28.8	32.0	24.9	14.2	4.9	3.9	4.8	10.8	20.8	29.7
Green @Tukwila	58.6	39.1	44.2	43.9	33.1	26.2	10.4	7.2	9.6	17.5	30.4	49.8
Hangman @Mouth	3.8	8.6	17.2	8.3	2.9	1.8	0.5	0.2	0.3	0.3	0.7	1.2
Hoh @DNR Campground	76.2	55.8	59.2	60.6	56.6	46.7	38.2	26.7	19.7	65.1	96.5	88.9
Humptulips nr Humptulips	45.3	45.9	37.1	32.0	14.6	11.2	5.9	4.1	5.6	21.5	61.6	45.4
Kalama nr Kalama	40.8	28.6	37.1	31.1	25.1	10.5	5.6	4.8	6.2	10.3	26.0	27.1
Little Spokane nr Mouth	14.1	14.4	23.9	23.2	19.1	14.3	11.6	10.5	10.4	11.1	12.1	13.3
Methow nr Pateros	11.8	9.8	12.4	34.1	92.9	157.1	50.4	15.9	9.7	10.5	11.9	11.2
Methow @Twisp	8.7	8.2	9.6	35.0	85.5	162.2	50.1	15.3	8.3	8.2	10.6	10.7
Naselle nr Naselle	14.0	10.1	14.7	10.3	4.1	2.6	1.3	0.9	0.7	6.3	24.8	19.5
N.F. Stillaguamish @Ciscero	60.9	40.2	61.7	56.5	47.8	32.8	15.5	10.2	9.0	41.1	69.2	59.9
N.F. Stillaguamish nr Darrington	18.0	10.7	19.0	15.6	15.3	7.0	3.4	2.3	2.0	8.5	15.8	17.1
Nisqually @Nisqually	75.5	63.7	65.8	48.9	46.9	39.2	33.3	26.3	27.6	36.7	55.9	74.7
Nooksack @No. Cedarville	99.7	63.0	76.6	103.5	130.8	107.9	74.7	45.3	34.5	80.7	100.2	99.7
Palouse @Hopper	14.9	23.3	30.3	27.6	12.5	8.2	2.3	0.8	1.0	1.4	3.0	5.4
Palouse @Palouse	6.2	20.0	15.6	18.3	8.2	5.8	1.0	0.5	0.4	1.0	1.2	2.6
Puyallup @Meridian St.	101.6	83.4	102.6	86.5	105.3	99.2	73.5	51.5	32.4	47.8	75.2	89.2
Samish nr Burlington	14.0	7.3	9.3	6.7	4.0	2.4	1.3	1.0	0.9	4.2	7.9	10.6
S. F. Palouse @Pullman	1.0	1.9	2.6	1.2	0.7	0.4	0.1	0.1	0.2	0.2	0.3	0.5
S. F. Stillaguamish @Arlington	62.6	28.7	50.5	57.2	45.3	30.6	12.5	7.7	8.8	36.8	43.3	34.8
S. F. Stillaguamish nr Granite Falls	34.8	17.1	22.6	27.9	53.5	22.1	11.7	6.3	6.8	44.8	26.7	17.6
Skagit @Marblemount	238.3	206.0	162.0	148.4	177.0	157.8	166.6	114.9	113.4	140.1	191.4	165.6
Skagit nr Mount Vernon	543.6	410.8	399.2	440.3	501.1	528.0	414.4	260.2	204.1	331.3	506.8	419.0
Skokomish nr Potlach	43.6	40.9	37.9	27.7	17.3	11.4	7.5	6.1	5.6	16.0	42.5	34.8
Skykomish @Monroe	167.0	117.2	153.5	179.5	248.6	161.9	78.1	41.3	41.9	124.3	167.6	150.1
Snohomish @Snohomish	278.0	195.	304.8	288.7	370.5	235.7	121.7	60.6	65.1	151.6	349.7	268.5
Snoqualmie nr Monroe	123.2	90.6	150.1	97.3	145.0	86.6	36.8	22.9	22.9	72.6	132.5	94.9
Snoqualmie @Snoqualmie	72.6	49.1	74.3	71.6	101.6	72.2	30.3	15.4	15.9	40.5	71.6	63.1
Spokane @Riverside St. Park	105.3	175.0	188.7	349.7	430.4	225.9	76.7	30.4	35.7	60.6	71.6	113.3
Spokane @Stateline Bridge	123.7	172.3	178.4	359.6	414.8	181.2	63.4	20.5	17.9	49.5	66.0	100.5
Stillaguamish nr Silvannia	118.9	79.3	103.2	103.3	93.3	73.3	26.8	15.8	16.3	93.4	130.8	131.9
Tucannan @Powers	3.6	3.9	5.1	6.4	7.0	6.0	2.0	1.6	1.6	2.1	2.5	3.0
Walla Walla nr Touchet	17.8	21.4	32.3	26.8	19.2	10.0	1.2	0.3	0.7	1.0	2.8	11.3
Wenatchee nr Leavenworth	25.1	26.1	29.7	62.4	132.1	184.2	71.6	23.8	14.0	13.2	29.7	26.3
Wenatchee @Wenatchee	41.1	43.7	47.1	101.5	172.7	247.2	94.8	27.1	14.8	16.0	36.8	43.9
Willapa nr Willapa	22.4	20.4	23.4	12.5	5.1	2.9	1.3	0.8	0.9	7.4	27.0	26.6
Yakima nr Cle Elum	14.8	14.9	15.1	26.9	16.4	20.1	19.7	19.7	14.8	9.2	11.6	12.5
Yakima @Kiona	66.1	81.4	101.1	107.6	86.7	75.3	39.6	37.2	48.7	47.0	63.7	67.7
Yakima @Nob Hill	67.0	75.5	72.8	135.1	124.2	157.8	106.2	98.7	79.8	59.5	42.3	55.2

Table B-8. Nitrogen loading metrics for western Washington watersheds.

Monitoring Station	Population (No.)	Municipal Surface Discharge (m^3/yr)	Municipal Land Discharge (m^3/yr)	Dairies / Cows (No.)	Beef Cows (No.)
Cedar @Logan	72,260	==	==	==	981
Chehalis @Dryad	2,034	297,764	==	==	1461
Cowlitz @Kelso	51,796	13,149,285	==	13 / 3,511	15,050
Deschutes @East Bridge	46,069	==	==	2 / 1,007	2,324
E. F. Lewis nr Dollar Corner	10,305	==	==	==	1,992
Elwha nr Port Angles	743	==	==	==	420
Green @Kanaskat	1,451	==	==	==	1,305
Green @Tukwila	297,025	==	==	11 / 3,805	2,554
Hoh @DNR Campground	128	==	==	==	233
Humptulips nr Humptulips	638	==	==	==	436
Kalama nr Kalama	4,021	==	==	==	647
Naselle nr Naselle	251	==	==	==	277
NF Stillaguamish @Ciscero	3,574	==	==	1 / 452	2,673
NF Stillaguamish nr Darrington	1,167	==	==	==	864
Nisqually @Nisqually	72,546	305,832	287,136	==	5,329
Nooksack @No. Cedarville	8,166	==	==	3 / 1,315	10,886
Puyallup @Meridian St.	208,731	7,259,844	==	15 / 7,230	4,858
Samish nr Burlington	6,412	==	==	1 / 481	1,189
SF Stillaguamish @Arlington	13,119	==	==	2 / 905	2,499
SF Stillaguamish @Granite Falls	1,559	==	==	==	1189
Skagit @Marblemount	1,409	16,628	==	==	18,837
Skagit nr Mount Vernon	42,502	3,840,065	==	9 / 4,329	35,682
Skokomish nr Potlatch	1,319	==	==	==	378
Skykomish @Monroe	16,347	528,101	==	2 / 905	6,325
Snohomish @Snohomish	182,856	7,816,023	==	13 / 5,348	12,952
Snoqualmie nr Monroe	67,843	2,973,322	==	6 / 2,182	3,938
Snoqualmie @Snoqualmie	13,877	715,429	==	==	2,046
Stillaguamish nr Silvannia	25,205	1,618,204	==	4 / 1,809	5,755
Willapa nr Willapa	858	==	==	1 / 1,434	639

Table B-9. Nitrogen loading metrics for eastern Washington watersheds.

Monitoring Station	Population (No.)	Municipal Surface Discharge (m^3/yr)	Municipal Land Discharge (m^3/yr)	Dairies / Cows (No.)	Beef Cows (No.)
Crab nr Beverley	92,974	68,839	133,600	28 / 23,406	149,554
Entiat nr Entiat	1,690	==	==	==	240
Hangman @Mouth	55,852	2,936,571	92,612	==	5,340
Little Spokane nr Mouth	107,451	8,023	520,204	5 / 1,168	6,655
Methow @Pateros	6,818	210,243	==	==	14,921
Methow @Twisp	3,982	86,888	==	==	10,480
Palouse @Hopper	55,860	5,781,503	237,460	3 / 234	18,784
Palouse @Palouse	255	166,173	==	==	*
SF Palouse @Pullman	13,269	3,140,961	==	==	184
Spokane @Riverside	323,941	68,031,438	==	==	*
Tucannan @Powers	1,748	201,687	==	==	4,499
Walla Walla nr Touchet	57,923	9,311,249	44,790	==	18,690
Wenatchee@ Leavenworth	1,768	60,575	==	==	384
Wenatchee @Wenatchee	20,661	1,074,833	20,222	==	761
Yakima nr Cle Elum	1,338	149,560	==	==	3,090
Yakima @Kiona	293,202	28,978,862	==	71 / 80,516	147,620
Yakima @Nob Hill	93,134	7,971,195	==	1 / 414	67,691

- Majority of watershed outside of state

Table B-10. Western Washington study watersheds groundwater nitrate concentration percentiles.

Drainage Name	n	Percentile Nitrate Concentration (mg/L)																
		90th	85th	80th	75th	70th	65th	60th	55th	50th	45th	40th	35th	30th	25th	20th	15th	10th
Cedar	61	1.65	1.30	1.10	0.93	0.82	0.80	0.70	0.54	0.50	0.50	0.50	0.47	0.45	0.40	0.30	0.20	0.20
Cowlitz	232	1.61	1.30	1.10	0.96	0.90	0.75	0.64	0.53	0.48	0.41	0.40	0.38	0.35	0.31	0.28	0.20	0.18
Deschutes	115	3.58	3.19	2.83	2.52	2.09	1.90	1.79	1.60	1.30	1.11	1.00	0.95	0.71	0.65	0.40	0.22	0.16
Green @Tukwila	161	3.11	2.40	1.84	1.35	1.10	0.85	0.67	0.50	0.46	0.30	0.22	0.20	0.20	0.20	0.20	0.20	0.20
Nisqually	230	3.75	3.36	2.81	2.23	1.77	1.27	1.02	0.76	0.59	0.50	0.47	0.37	0.31	0.24	0.20	0.20	0.20
Nooksack	29	0.93	0.89	0.82	0.81	0.80	0.80	0.74	0.71	0.70	0.68	0.65	0.63	0.60	0.52	0.50	0.50	0.38
Puyallup	115	4.46	3.51	1.84	1.37	1.21	0.84	0.66	0.51	0.34	0.28	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SF Stillaguamish @Arlington	29	3.84	3.39	2.70	2.03	1.77	1.37	0.80	0.56	0.43	0.41	0.38	0.36	0.28	0.20	0.15	0.06	0.05
Skagit @Mt Vernon	55	1.75	1.19	1.07	0.91	0.64	0.55	0.49	0.45	0.40	0.36	0.35	0.33	0.31	0.27	0.25	0.21	0.19
Skykomish @Monroe	27	1.07	0.83	0.80	0.79	0.74	0.60	0.55	0.52	0.50	0.46	0.45	0.43	0.42	0.40	0.37	0.36	0.19
Snohomish @Snohomish	167	2.52	1.92	1.47	1.25	0.98	0.82	0.76	0.60	0.50	0.50	0.43	0.39	0.36	0.30	0.20	0.05	0.05
Snoqualmie @Snoqualmie	31	1.70	1.14	1.05	0.97	0.83	0.83	0.78	0.74	0.70	0.64	0.58	0.49	0.43	0.42	0.39	0.37	0.30
Snoqualmie @Monroe	64	2.07	1.79	1.51	1.13	0.98	0.83	0.78	0.70	0.65	0.53	0.50	0.48	0.42	0.40	0.37	0.35	0.30
Stillaguamish @Silvannia	56	3.68	3.40	2.66	2.07	1.55	1.04	0.60	0.51	0.50	0.46	0.42	0.39	0.36	0.22	0.07	0.05	0.05

Table B-11. Eastern Washington study watersheds nitrate groundwater percentiles.

Drainage Name	n	Percentile Nitrate Concentration (mg/L)																
		90th	85th	80th	75th	70th	65th	60th	55th	50th	45th	40th	35th	30th	25th	20th	15th	10th
Crab	240	12.74	9.61	7.99	7.33	6.59	6.11	5.32	4.49	4.10	3.65	3.24	2.88	2.30	1.95	1.36	0.72	0.24
Entiat	15	1.33	0.97	0.75	0.61	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.44
L. Spokane	75	9.20	7.19	5.07	4.60	3.94	3.65	3.28	2.78	2.04	1.92	1.55	1.42	0.83	0.73	0.58	0.50	0.46
Methow @Pateros	77	1.64	1.34	0.90	0.67	0.48	0.44	0.40	0.37	0.28	0.26	0.24	0.21	0.20	0.19	0.14	0.12	0.10
Methow @Twisp	67	1.62	1.32	0.90	0.59	0.47	0.43	0.37	0.30	0.26	0.25	0.23	0.20	0.19	0.18	0.14	0.12	0.10
Palouse @Hopper	73	9.64	7.71	6.46	6.13	4.92	4.21	3.16	2.75	2.58	2.11	1.29	0.86	0.50	0.34	0.14	0.10	0.05
Spokane @Riverside	81	3.23	2.86	2.50	2.41	2.15	1.92	1.65	1.58	1.46	1.40	1.30	1.25	1.09	1.00	0.89	0.64	0.48
Walla Walla	55	9.92	8.51	6.22	5.08	4.72	4.29	3.25	3.01	2.06	1.93	1.66	1.53	0.84	0.65	0.46	0.18	0.05
Wenatchee @Leavenworth	50	1.11	1.00	0.93	0.79	0.79	0.75	0.61	0.54	0.46	0.37	0.30	0.26	0.19	0.15	0.12	0.09	0.03
Wenatchee @Wenatchee	143	4.39	3.70	3.41	2.81	2.10	1.70	1.31	1.07	0.99	0.79	0.75	0.66	0.57	0.42	0.30	0.18	0.09
Yakima @Cle Elum	22	0.50	0.49	0.43	0.40	0.40	0.38	0.35	0.29	0.22	0.21	0.20	0.19	0.18	0.18	0.17	0.12	0.11
Yakima @Kiona	883	4.73	4.00	3.47	3.10	2.80	2.45	2.20	1.90	1.65	1.40	1.12	0.89	0.70	0.50	0.35	0.23	0.11
Yakima @Nob Hill	196	3.60	3.25	2.52	2.10	1.60	1.37	1.09	0.87	0.72	0.54	0.46	0.40	0.35	0.29	0.22	0.18	0.10

Table B-12. Yakima HUCs groundwater nitrate percentiles.

HUC	n	Percentile Nitrate Concentration (mg/L)																	
		95th	90th	85th	80th	75th	70th	65th	60th	55th	50th	45th	40th	35th	30th	25th	20th	15th	10th
Ahnathum	22	3.73	3.65	3.18	2.49	2.32	2.01	1.85	1.60	1.30	1.15	0.92	0.76	0.56	0.43	0.36	0.30	0.24	0.22
Cle Elum	3	1.44	1.32	1.20	1.08	0.96	0.84	0.72	0.60	0.48	0.36	0.34	0.32	0.31	0.29	0.28	0.26	0.25	0.23
Corral	37	11.4	7.46	6.08	5.15	4.67	4.14	3.41	3.15	2.28	1.90	1.33	1.11	0.85	0.37	0.20	0.12	0.10	0.10
Deep Canyon	80	17.2	6.36	5.05	4.01	3.28	2.72	2.04	1.76	1.46	1.29	1.06	0.90	0.76	0.70	0.59	0.43	0.30	0.20
Kachess	27	0.80	0.68	0.51	0.49	0.42	0.40	0.40	0.35	0.35	0.22	0.21	0.20	0.20	0.18	0.18	0.17	0.12	0.11
L. Naches	13	0.45	0.42	0.38	0.36	0.35	0.35	0.35	0.34	0.33	0.33	0.33	0.32	0.31	0.31	0.30	0.27	0.26	0.26
Marion Drain	305	5.21	4.73	4.30	3.85	3.40	3.10	2.90	2.70	2.50	2.35	2.10	1.90	1.80	1.60	1.40	1.20	1.06	0.76
Rattlesnake	14	1.20	1.00	0.63	0.57	0.54	0.51	0.48	0.44	0.38	0.34	0.30	0.28	0.26	0.24	0.16	0.12	0.11	0.07
Simcoe	47	3.44	1.76	1.33	0.98	0.87	0.78	0.75	0.70	0.69	0.60	0.47	0.33	0.30	0.30	0.26	0.15	0.11	0.10
Spring	67	14.33	10.85	6.31	4.71	3.20	2.58	2.31	2.17	1.93	1.73	0.69	0.57	0.31	0.10	0.06	0.04	0.01	0.01
Sunnyside	19	20.33	16.41	15.01	11.95	9.55	8.63	7.97	7.85	7.36	3.79	3.22	2.85	2.56	2.10	1.77	1.10	0.22	0.20
Taneum	20	5.15	3.44	2.87	2.18	1.65	1.44	1.39	1.39	1.23	1.05	0.91	0.62	0.37	0.33	0.29	0.27	0.26	0.24
Tieton	57	4.86	4.35	4.05	3.77	3.63	3.56	3.41	3.29	3.14	2.79	2.52	2.28	2.09	1.87	1.59	1.35	0.97	0.76
Toppenish	80	4.44	4.00	3.00	2.52	2.05	1.85	1.54	1.40	1.15	1.00	0.84	0.71	0.40	0.27	0.20	0.10	0.10	0.07
Umtanum	12	3.54	3.12	2.56	2.09	1.75	1.59	1.56	1.52	1.47	1.39	1.30	1.23	1.15	1.07	0.99	0.90	0.76	0.58
Wide Hollow	81	5.38	4.88	4.17	3.50	3.35	3.10	3.03	2.80	2.60	2.40	2.04	1.45	1.13	0.93	0.64	0.36	0.10	0.10
Wilson	20	3.47	2.37	2.23	2.14	1.42	1.06	0.83	0.72	0.64	0.58	0.54	0.51	0.49	0.45	0.41	0.32	0.27	0.08

Table B-13. Groundwater nitrate percentiles for the Nooksack and Sumas River HUCs.

HUC	n	Percentile Nitrate Concentration (mg/L)																	
		95th	90th	85th	80th	75th	70th	65th	60th	55th	50th	45th	40th	35th	30th	25th	20th	15th	10th
Lower NF Nooksack	17	1.09	0.97	0.90	0.89	0.83	0.81	0.80	0.80	0.80	0.80	0.74	0.71	0.70	0.69	0.65	0.65	0.62	0.60
Nooksack – Frontal Bellingham	586	17.08	14.25	11.93	9.76	7.95	6.36	5.22	4.02	3.22	2.66	2.01	1.50	0.94	0.58	0.32	0.16	0.10	0.06
Sumas	95	17.2	15.17	14.28	12.84	9.44	6.71	5.42	4.54	3.63	3.15	2.77	2.12	1.77	1.22	0.79	0.29	0.10	0.07

Table B-14. Groundwater nitrate percentiles for the Crab Creek HUCs.

HUC	n	Percentile Nitrate Concentration (mg/L)																	
		95th	90th	85th	80th	75th	70th	65th	60th	55th	50th	45th	40th	35th	30th	25th	20th	15th	10th
Crab-Pothole	38	24.80	20.07	13.51	11.10	7.87	6.16	5.49	4.51	3.70	3.51	3.36	3.20	3.00	2.39	1.83	1.44	0.70	0.18
Frenchman	52	28.73	15.28	9.74	8.76	7.99	7.66	7.30	6.52	6.18	5.91	4.99	4.47	3.93	3.78	3.34	3.01	2.37	1.34
Lind Coulee	14	8.72	8.08	8.02	7.93	7.83	7.73	6.64	5.74	5.63	5.13	4.63	4.48	4.35	4.12	3.24	2.88	2.84	2.68
Lower Crab	38	18.38	12.94	11.50	9.29	8.19	7.70	6.98	6.19	5.90	5.25	4.32	3.88	3.07	2.61	1.65	1.38	1.06	0.73
Rocky Ford	14	6.50	5.81	4.87	4.61	4.00	2.74	2.38	2.24	2.20	2.08	1.87	1.44	1.19	0.97	0.48	0.22	0.09	0.06
Round Lake	20	7.35	7.10	6.86	6.70	6.03	5.56	5.37	4.90	4.56	4.35	4.16	3.92	3.15	2.30	2.29	2.28	2.16	1.74
Winchester Waste-way	26	28.48	14.15	11.29	9.57	8.49	7.58	7.18	4.70	4.11	3.84	3.78	3.52	3.22	2.97	2.34	0.72	0.03	0.02

Appendix C. Watershed Patterns in Flow and Nitrate Levels

The seasonal variation in flow and nitrate observed at the study monitoring locations is examined in this section. The objective of this analysis is to provide an understanding of the connection between a watershed's hydrology (whether natural or artificially-influenced) and corresponding nitrate levels, providing an initial diagnostic tool. Here the focus is not on the magnitude of flows and nitrate levels among the watersheds rather it is on finding commonality in the seasonal variation, providing insight into the dominant loading pathways present. In addition, once common seasonal patterns are identified, deviations from them provide insight into alternative loading pathways which can then be linked to specific types of nitrate sources.

Watershed Groups: common seasonal variation in flow and nitrate concentrations

Based on a comparison of the monthly variation in flow and nitrate among the study watersheds, five characteristic patterns were identified: three for watersheds situated in western Washington, and two for the east side. Table B-5 in Appendix B presents the western and eastern Washington watershed groups associated with each of the monitoring stations, along with the various flow and nitrate metrics presented in this discussion. In addition, the median monthly nitrate and ammonia concentrations applied in this analysis are included in Tables B-6 and B-7, respectively, in Appendix B. Median monthly flow levels are included in Table B-8. Within each group, the various watersheds do not necessarily share similar flow and nitrate levels rather, the groups are based on sharing a similar seasonal response between flow and corresponding nitrate concentrations. This portion of the overall analysis was undertaken to provide some perspective on the variation in these relationships occurring within Washington. Each watershed is unique. While common seasonal patterns were found for the majority of the study watersheds, others defied categorization due primarily to the fact that their flows are managed for irrigation or hydroelectric power generation, and therefore do not follow a natural runoff pattern.

Western Washington watershed groups

The major factor distinguishing western Washington watersheds is the level of winter snow storage which is a function of elevation, magnitude of precipitation, and proximity. Three flow groups were formed and are referred to as low, medium, and high elevation watersheds. The distinguishing metric is the percent of the watershed area situated above 1,000-meters, the approximate average December through February freezing level. While the freezing level elevation varies during the winter, on average, above approximately 1000-meters, the precipitation is stored as snow until spring warming. This period coincides with peak annual precipitation levels in western Washington.

The low elevation watersheds are those with less than 5% of their area situated above 1,000-meters. These watersheds have no significant snow storage and their monthly flow variation is in direct response to the level of precipitation over the watershed.

The mid-elevation watersheds are those with between 5% and 20% of their elevations above 1,000-meters providing moderate snow storage during the winter. Importantly, these watersheds have the greatest percent of the watershed area within the 500 to 1,000-meter rain-on-snow zone, (with a median level of 40%) and are prone to losing snow storage due to warming weather systems potentially generating high magnitude runoff events during the winter.

The third group comprises drainages with greater than 20% of their watershed area situated above 1,000-meters. (Figure A-1 in Appendix A presents a cumulative frequency distribution of elevations characteristic of each of the western and eastern Washington groups.)

A complicating factor influencing seasonal flow patterns for both western and eastern Washington watersheds are those with storage in the form of lakes or more commonly, reservoirs. Reservoir storage occurs within the Crab, Cedar, Cowlitz, Elwha, Green, Nisqually, Puyallup, Skagit, Skokomish, Wenatchee, and Yakima watersheds. The level of storage and the management of its outflow vary by watershed. Therefore, with no common defining flow pattern, these watersheds were placed into a catchall group referred to as storage. The majority of these stations are managed for flood control (Puyallup), water supply (Cedar, Green), irrigation (Crab, Yakima), or hydroelectric power generation (Skokomish, Nisqually, Cowlitz, Skagit). Many of the watersheds within this group would normally be placed into the high elevation group. For instance, both the Nisqually and Cowlitz watersheds have about 25% of their drainage area situated above 1,000-meters. While both of these watersheds include significant spring snow-melt, its translation to the lower basin (where the monitoring stations are located) is significantly dampened due to reservoir storage and outflow management. The end result is that the natural spring period hydrograph is altered to the extent that it mimics that of the lower elevation drainages. Therefore, each of these storage (or managed watersheds) is unique requiring independent examination.

The groundwater group is another catch-all group. The watersheds included in this group are those where the seasonal variation in nitrate loading is heavily influenced by groundwater discharge, typically with elevated concentrations, but its members do not necessarily share common seasonal patterns.

The percent of the annual flow occurring each month for the low, middle, and high elevation watersheds groups are included in Figure C-1. A relative reference to these flow patterns was used to account for varying drainage areas. Drainages comprising the low elevation group have limited winter-time storage in the form of snow, resulting in more immediate surface runoff in response to precipitation events. For these watersheds, about 76% of the total annual runoff occurs November-March, coinciding with higher precipitation levels. In comparison, the middle and high elevation watersheds, during this same period, are storing precipitation at elevations above 1,000 meters resulting in about 63% and 46% of their total annual runoff occurring November to March, respectively. Median monthly flows peak in the low elevation watersheds in November / December, declining through spring as precipitation levels also decline. Base flows are defined here as the lowest monthly median flows that occur in the annual cycle and typically occur for all three western Washington watershed groups during the months of August and September. This is a period when the majority of the flow is comprised of groundwater discharge. The August / September total flow, as a percent of the total annual flow, is 5%, 4%, and 2% for the high, medium, and low elevation groups.

The peak flow for the high elevation watersheds occurs in May when 14% of the annual total discharge occurs and is related to spring snowmelt. Following the peak, flows decline at a lower rate in comparison to the other groups, particularly the low elevation group, due to continued snowmelt and upper basin groundwater discharge.

The middle elevation group has flow variation right in the middle of the other two groups that are affected by the storage of snow. While its peak monthly flow is also associated with snowmelt, precipitation events is also an important factor since the March flow peak is not that much greater than the levels observed in November and December. This is indicated by the increase in flow for October and November for both the middle and high elevation watersheds. Snow storage and its melting in addition to groundwater discharge over the spring and summer maintain flows at higher levels in comparison to the low elevation watersheds.

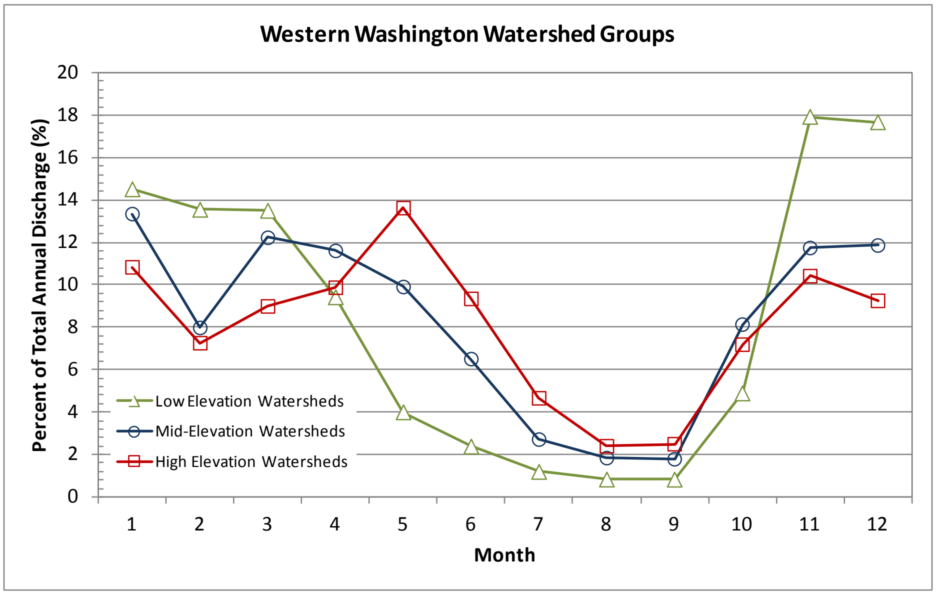


Figure C-1. The percent of the annual total runoff occurring monthly for the western Washington watersheds.

A watershed representative of each group is presented along with an overview of their characteristic flow and nitrate variation.

Low elevation watersheds

Each watershed group's distinct seasonal flow variation influences nitrate concentrations. The median monthly flow and nitrate levels for the low elevation drainages are presented in Figures C-2 and C-3, respectively. All of these watersheds have a positive correlation between the level of flow and observed nitrate concentrations. The variation in the median monthly flows (cms=cubic meters per second - m^3/s) and nitrate concentrations for the Chehalis River @Dryad present a typical relationship for these watersheds (Figure C-4). As previously discussed, snow accumulation in these watersheds is minor and the magnitude and seasonal variation in precipitation forms the major determinant on flow variation. Therefore, the dominant pathway of nitrate movement to surface waters is direct land surface runoff. Greater levels of runoff result in higher interception and delivery of nitrate so peak loading is coincident with the highest flows. This occurs November through February. With diminishing flows, April through September, nitrate concentrations decline only to increase again with increasing precipitation and associated flow in October. The lowest concentrations occur at base-flow indicating that groundwater discharge is typically not a major source of nitrate for these watersheds. This is not always the case for the low elevation-type watersheds. In particular, among the study watersheds, both the Samish and Deschutes would normally be classified as low elevation-type watersheds yet due to the intersection of soil characteristics which influence the infiltration of precipitation, along with elevated nitrate loading to the land surface has resulted in groundwater contamination. Now, groundwater discharge is a major source of nitrate to surface water in each of these watersheds. These watersheds will be discussed in more detail shortly.

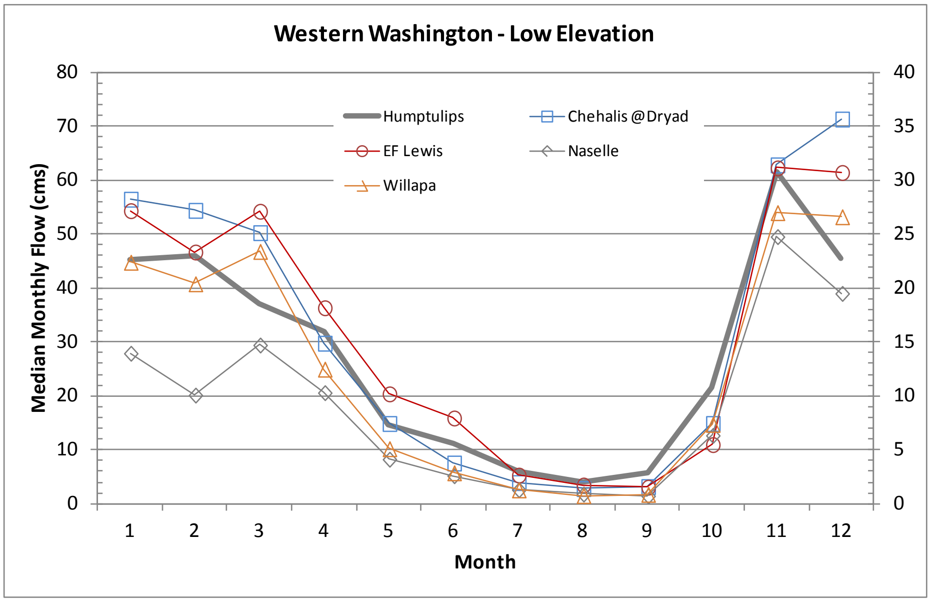


Figure C-2. Median monthly flow levels observed for the western Washington low elevations watersheds.

As observed in Figure C-3, the low elevation watersheds have varying monthly median nitrate concentrations reflective of differing loading intensities. The Humptulips watershed has the lowest overall nitrate concentration which reflects it having approximately 99% of its land use in forest-land, a background-type nitrate loading condition. While nitrate concentrations increase in relation to increasing runoff, a characteristic common within all of these watersheds, it does so to a lower level for the Humptulips in comparison to the other watersheds. In comparison, the Willapa @Willapa and Chehalis @Dryad have a more pronounced increase in nitrate concentrations with changes in flow, reflective of higher representation of the forest as deciduous in addition to an increase in anthropogenic-derived sources.

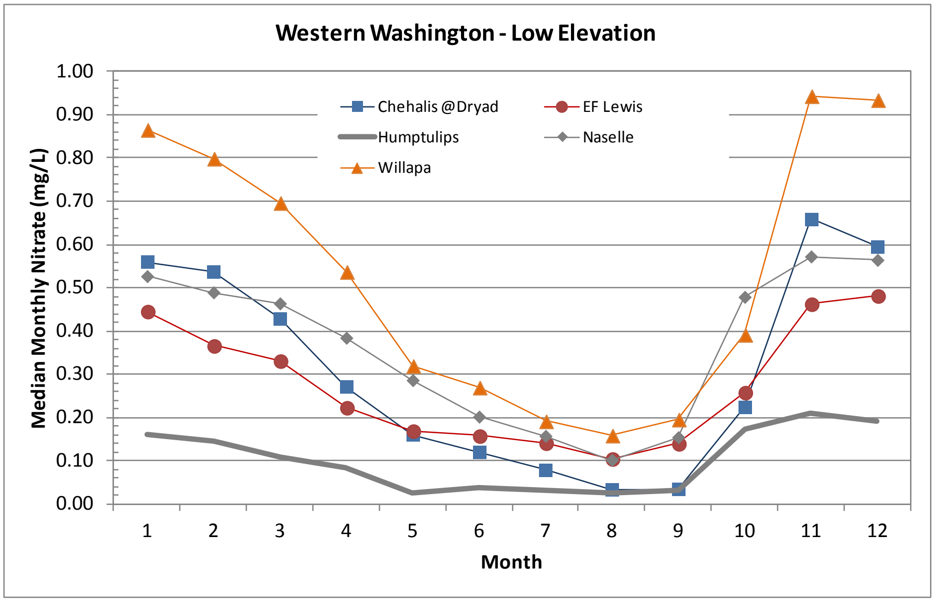


Figure C-3. Median monthly nitrate levels observed for the western Washington low elevation type watersheds.

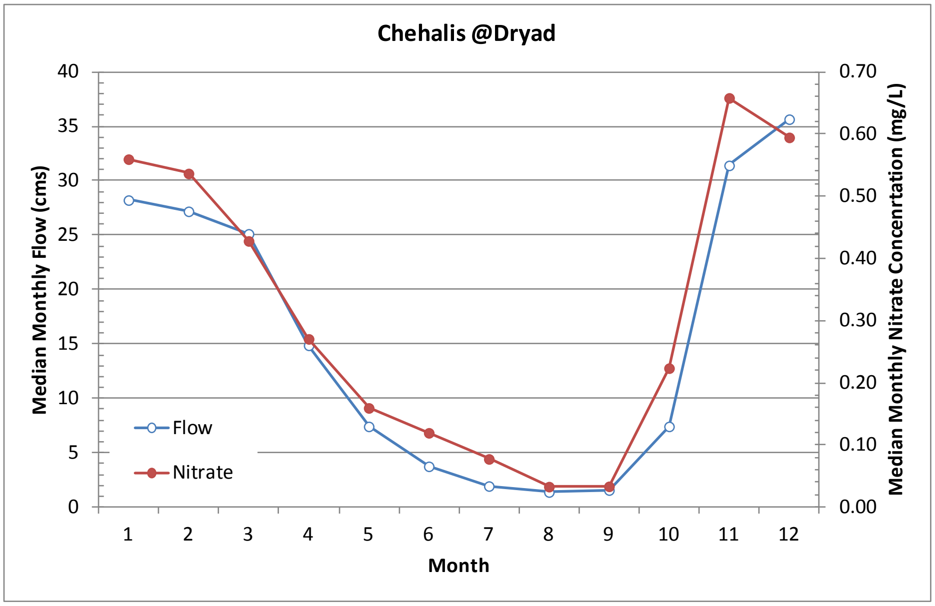


Figure C-4. Chehalis River @Dryad, an example of the type of response and monthly variation between flow and nitrate characteristic of the low elevation watersheds.

Mid-elevation watersheds

Figures C-5 and C-6 present the monthly median flow and nitrate levels observed for the mid-elevation watersheds. For additional clarity, these two parameters are plotted together for the North Fork Stillaguamish River @Ciscero as an example of the relationship characteristic of this group (Figure C-7). The watersheds representative of this group all share a close relationship between the level of flow and nitrate similar to that observed for the low elevation watersheds for much of the year. The lowest concentrations found at base flows in August / September increases significantly with increased precipitation October through December. From here the similarity between the groups diverge due to differences in elevation and resulting snow storage. This is evident from about December through February. The reason for the declining flow levels during this period is because precipitation is stored as snow instead of contributing directly to runoff in between 5 and 20% of the drainage area. Flow increases in March due to warming air temperatures, and the initiation of snow melt, which continues to be an important component of the overall stream flow into early summer. Over this period, nitrate concentrations decline at a faster rate than does flow. In comparison, the low elevation watersheds tend to have flow and nitrate highly correlated through varying flow levels because of the source of flow. Snow melt comprises the major source of spring flow and is low in nitrate. Flow generated by snow melt dilutes the nitrate introduced to the surface water by other pathways such as overland flow. The annual low flows and nitrate concentrations coincide during the summer base flow period indicating that groundwater contamination does not commonly occur for these watersheds.

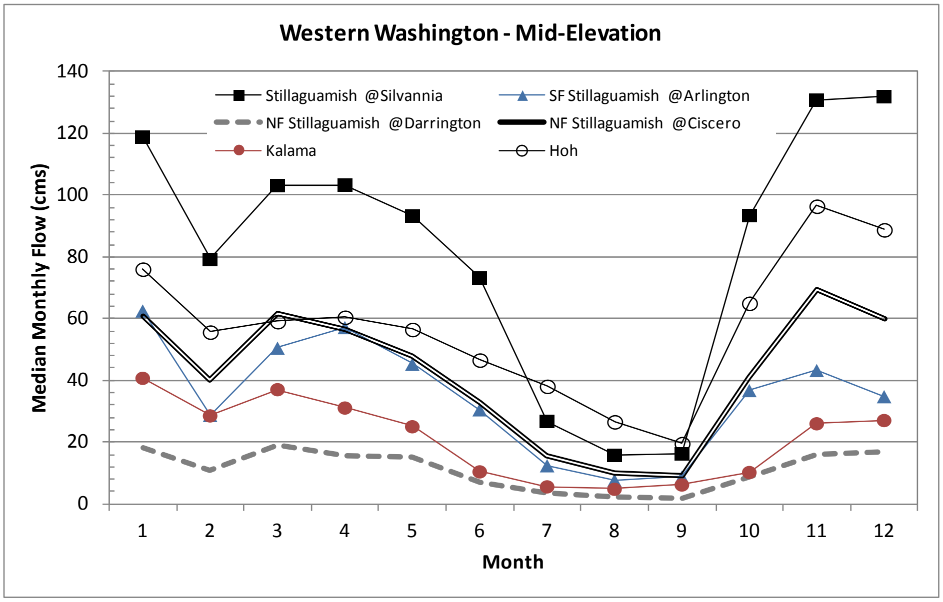


Figure C-5. Median monthly flow levels for the middle elevation watersheds.

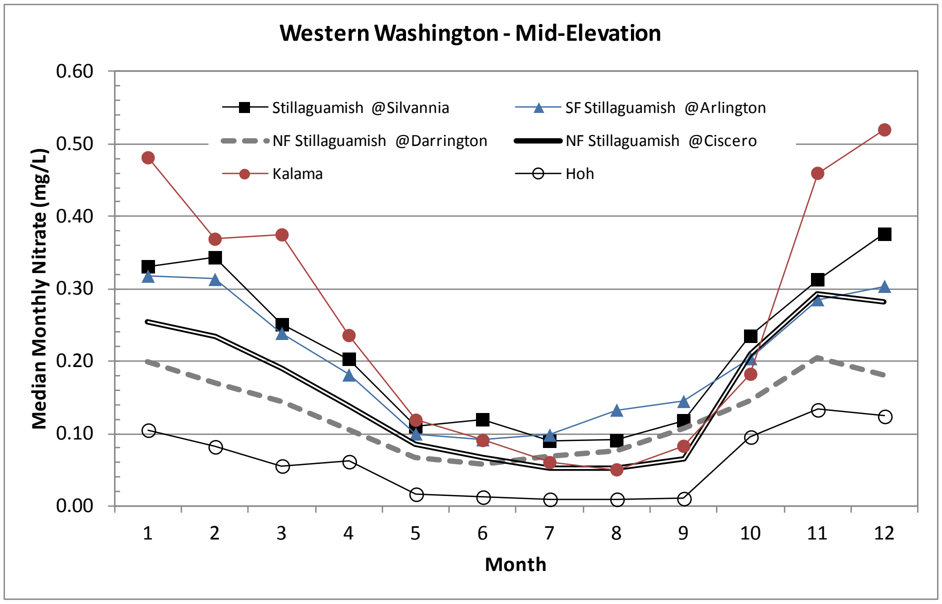


Figure C-6. Median monthly nitrate concentrations (mg/L) for the middle elevation watersheds.

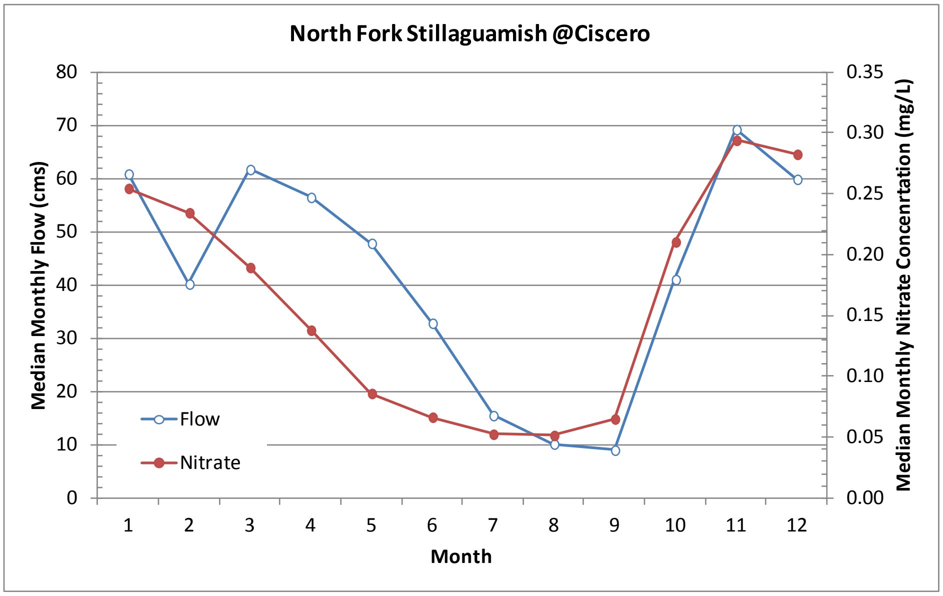


Figure C-7. The North Fork of the Stillaguamish River @Ciscero, an example of the middle elevation watershed response to flow and nitrate variation.

High elevation watersheds

Figures C-8 and C-9 present the monthly median flow and nitrate levels observed for the high-elevation watersheds. Both parameters are plotted together for the Nooksack @North Cedarville (Figure C-10). The overall pattern present for these watersheds is similar to the middle elevation watersheds but the increased percentage of the watershed situated at elevations exceeding 1,000 meters, in addition to the greater precipitation levels that occur there, results in the greater accumulation of snow. Together these factors result in a longer period that snow melt affects stream flow and nitrate levels. In the case of the Nooksack, snow melt begins to affect flows in March (when the middle elevation streams are at their snow melt peak) with a peak influence in May (Figure C-10). The middle elevation watersheds are an amalgam of the low and high elevation types of hydrologic influences: snow accumulation balanced with direct surface runoff. Flows observed for the high elevation watersheds are more dominated by snow melt. During the snow melt period, nitrate concentrations are inversely related to the level of flow. However, from October to December, the relationship between flow and nitrate is similar to that observed for the other groups indicating that the major sources of nitrate loading, even for these higher elevation watersheds, continues to be winter period surface runoff associated with nitrate-generating activities typically situated in the lower valleys. Even so, higher elevation snow-melt, which is low in nitrate, provides a buffer, diluting lower elevation loading for much of the year. For this reason, this group tends to have some of the lowest observed nitrate concentrations of the study watersheds.

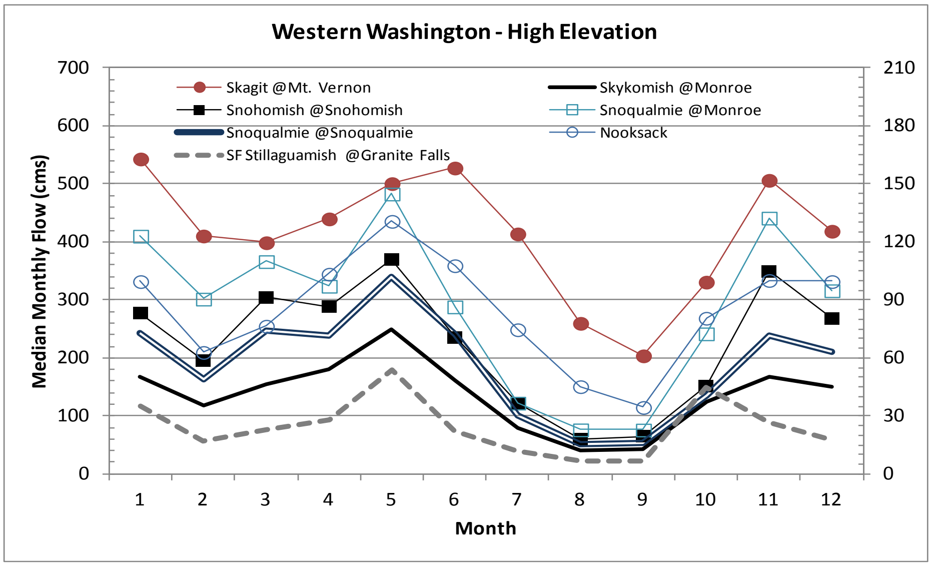


Figure C-8. Median monthly flow levels for the high elevation watersheds.

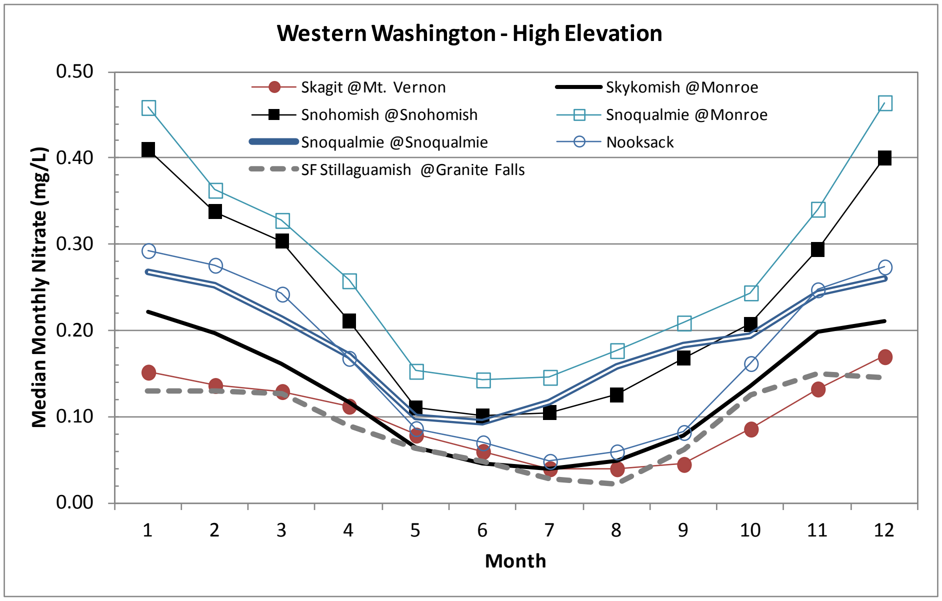


Figure C-9. Median monthly nitrate concentrations observed for the high elevation watersheds.

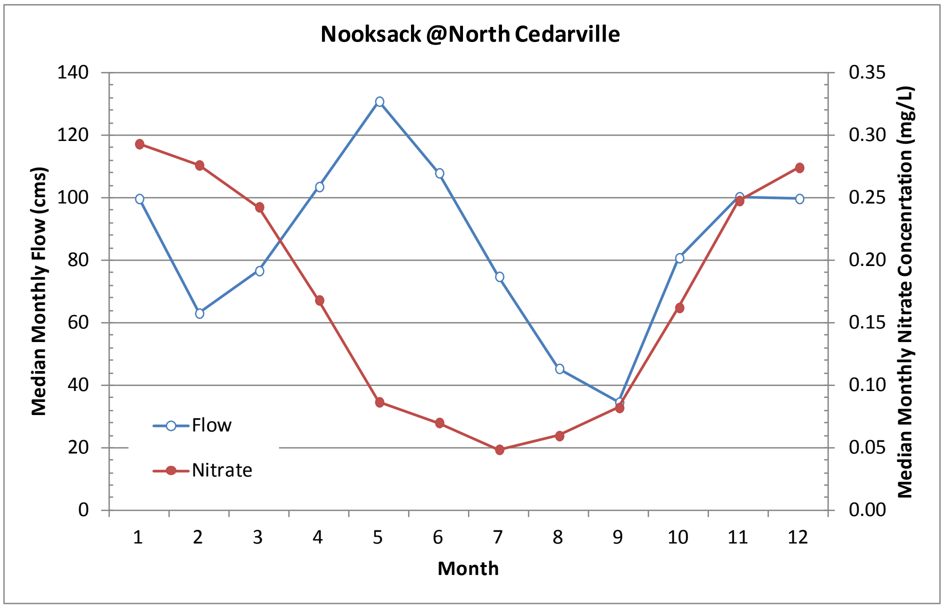


Figure C-10. Nooksack River @North Cedarville, an example of the monthly variation in flows and nitrate levels characteristic of the high elevation type watersheds.

Eastern Washington watershed groups

Two distinct groups were determined for the eastern Washington watersheds and are referred to as the eastern Cascade and Palouse. Watersheds draining from the eastern Cascades include the Wenatchee, Entiat, and Methow. All are watersheds that drain from the eastern slopes of the Cascades. This group should also include the Yakima given this geographic distinction. However, the Yakima is now a highly managed system in which the natural flow patterns have been altered to provide for irrigation. The Yakima River is a significant surface water body in Washington and so is examined as an entirely separate group. A similar distinction is also given to Crab Creek and the Spokane River. The other group is the Palouse and it includes the Walla Walla, Hangman, and Palouse watersheds.

Spring snow melt is a prominent feature in the seasonal flow pattern for all of the eastern Washington groups (Figure C-11). The distinction among them is in the timing to peak snow melt and its magnitude, again a function of elevation differences. For instance, the eastern Cascade drainages, with the greatest overall elevations, have their highest annual flow representation in June while the Palouse drainages have their annual flow peak two months prior in March. The percent of the watershed’s area above 1,000 meters for the east Cascade and Palouse groups is 69% and 12%, respectively. The Palouse is a relatively flat topography (plateau) with an approximately 700-meter overall median elevation (refer to Figure A1 in Appendix A). This topography results in a uniform response to spring warming throughout the drainage area in comparison to the eastern Cascades where the varied topographic relief provides a more measured release to snow melt. There is a median level of 67% of the watershed area for the Palouse watersheds situated between 500 and 1,000 meters indicating a vulnerability to rapid snow melt associated with warming weather systems during the winter. Also, both the eastern Cascade and Palouse drainages have the majority of their annual outflow occurring within a relatively brief period. Approximately 70% of the total annual discharge occurs between May and July for the eastern Cascade drainages while about 60% occurs between February-April for the Palouse drainages (Figure C-11).

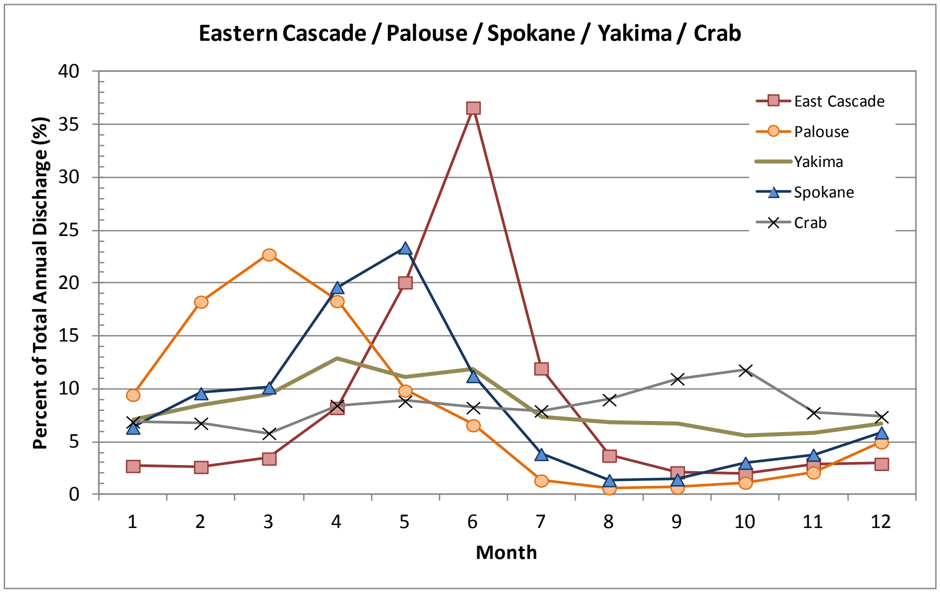


Figure C-11. Percent of the total annual flow occurring each month for the eastside drainage groups.

Flows of Crab Creek, Spokane and Yakima rivers are heavily managed and so are given their individual grouping. Crab Creek and the Yakima River flows are managed primarily for irrigation. In the case of the Yakima River, while a monthly flow variation similar to the eastern Cascade group would be expected, it is instead dampened, reducing the annual snow melt peak. Flow management results in a more even distribution of flow throughout the year damping the high spring snow melt period through upper watershed reservoir storage while increasing base flows through storage release for irrigation to meet agricultural demand in the lower valley. When the other eastern groups experience their annual low flows in August / September, the Yakima's flow representation is not much lower than at its peak in April (Figure C-11).

The origin of the Spokane River is the outlet of the massive Lake Coeur d'Alene in Idaho. The surface area of Lake Coeur d'Alene is 129 km^2 with a drainage area of 9,583 km^2 that extends into Montana. The lake receives high spring inflow associated with snow melt which is passed to the Spokane River. Peak flows in April / May account for approximately 40% of the total annual flow. From this spring peak, flows decline rapidly reaching annual lows, in July – September, a period which accounts for just 6% of the annual flow total.

Palouse Watersheds

Figures C-12 and C-13 present the monthly median flow and nitrate levels observed for the Palouse watersheds. The Palouse watershed group is regionally-based and distinguished by its exceptionally low water yields, almost an order of magnitude lower in comparison to the other eastern Washington groups at base-flow. Precipitation levels within the greater Palouse are among the lowest in Washington and irrigation is not a prominent feature for the majority of the drainages represented. Therefore, dilution of point and nonpoint source nitrate loading is at a minimum leading to among the greatest observed nitrate concentrations of the watersheds examined by this study (Figure C-13). While snow melt provides an approximately three month dilution effect on observed nitrate concentrations, for the remainder of the year, there is a positive relationship between flow and nitrate levels indicating that the main nitrate loading pathway is overland flow (mainly associated with nonpoint sources) in addition to direct discharge from point sources.

Much of the greater Palouse, though having rolling terrain, is relatively uniform in elevation over a wide area. The average elevation is high enough that there is moderate winter snow accumulation though low enough for rapid melting to occur associated with winter-spring warming events. This is indicated by the increasing flow levels that occur December to February a period when typically snow accumulation would be expected. Nitrate concentrations also increase and reach a peak level coinciding with increasing flows which indicates that the primary nitrate loading pathway is overland flow.

An interesting characteristic common to the Palouse watersheds is that changes in stream nitrate levels precede changes in flow by about one month. This is present for the Palouse @Hopper, South Fork Palouse, and Walla Walla monitoring locations. Nitrate concentration changes precede flow by two months for the Palouse @Palouse and by three months for the Tucannon. Considering the monthly variation in precipitation, flow, and nitrate for the Walla Walla, and focusing on the increases in nitrate levels from November through February, flow follows precipitation by about two months and nitrate follows precipitation by about one month. So it appears that precipitation is leaching nitrate from soils, likely derived from fall period wheat fertilization. Interflow, derived from precipitation, is then delivered to these streams at a faster rate than the big driver of flow modification, surface runoff. The lag between precipitation and flow could be a result of storage within a frozen upper soil horizon and (or) as snow. The Palouse @Hopper monitoring station is an example of the relationship between flow and nitrate levels characteristic of the Palouse watersheds (Figure C-14).

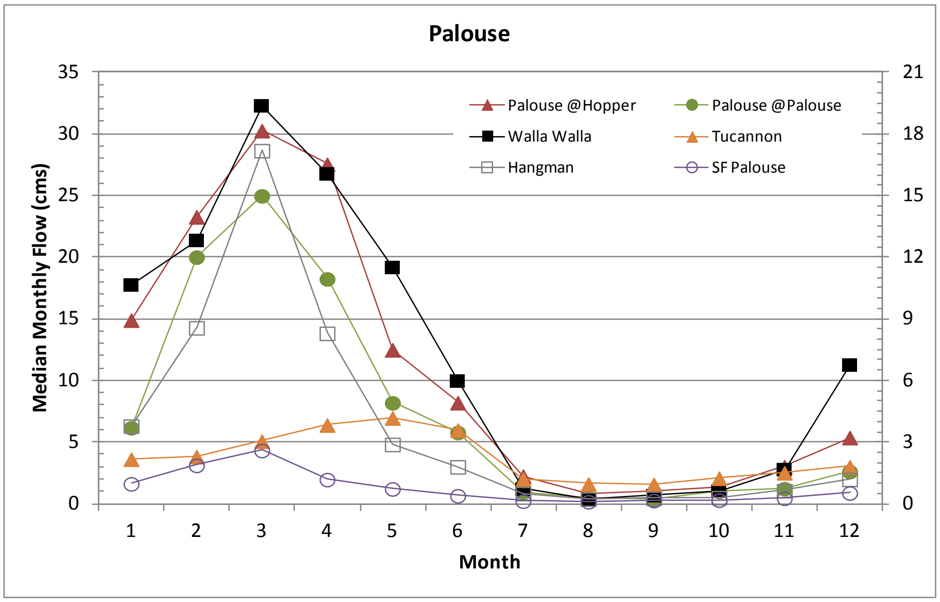


Figure C-12. Palouse grouping of study watersheds and their respective median monthly flow levels. (Solid symbols refer to left hand scale.)

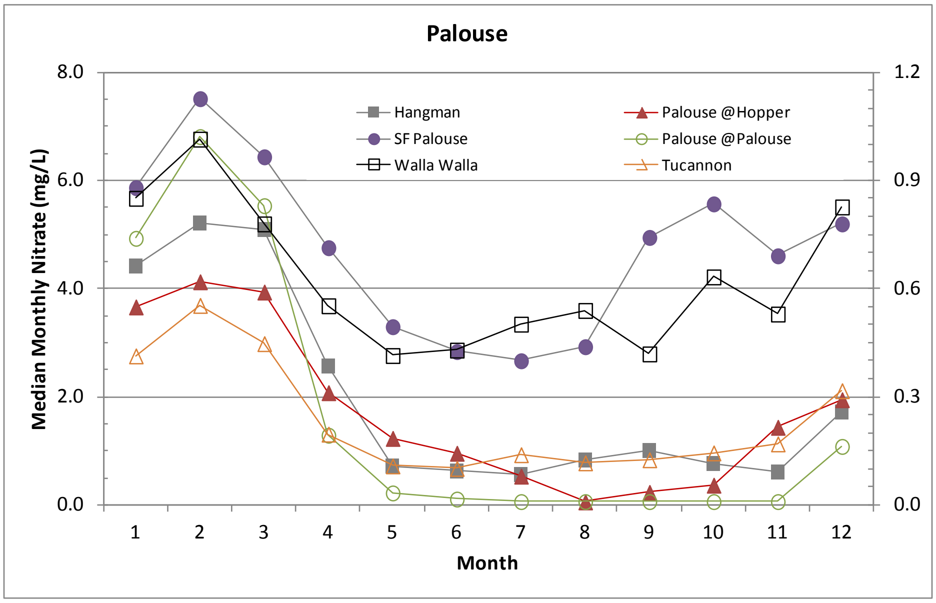


Figure C-13. Palouse grouping of study watersheds and their respective median monthly nitrate concentrations. (Solid symbols refer to left hand scale.)

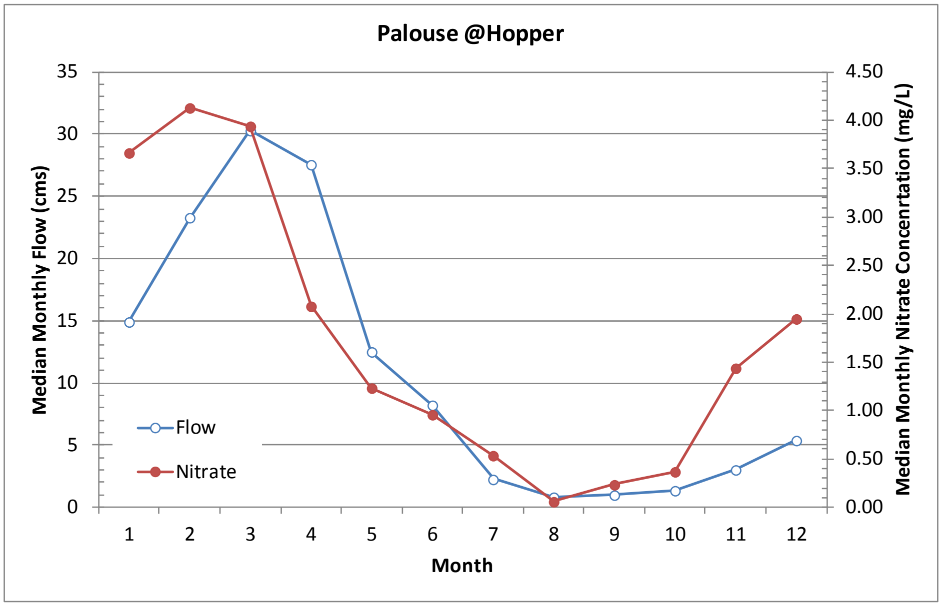


Figure C-14. Monthly nitrate and flow variation: the Palouse River @Hopper.

The snow-melt peak typically occurs in March followed by rapidly declining flows through July with the base-flow period occurring August – October. Similar to the western Washington surface runoff drainages, the Palouse drainages have a close association between the level of flow and associated nitrate concentrations though the magnitude of the nitrate concentrations are significantly higher due to the lower overall water yield. Another significant difference is that the snow is deposited within nitrate-generating land uses, primarily wheat production. This differs from the east Cascade and middle and high elevation watersheds in western Washington where snow storage occurs in upper elevation forest-lands, which essentially serve as a background reference for nitrate loading. So while with many of the other watershed groups the increased flow associated with snow melt serves to dilute stream nitrate concentrations, in the case of the Palouse, due to its topography and land use characteristics, this occurs to a lower degree. The seasonal flow pattern for the Tucannon River differs from the other Palouse watersheds. Despite this difference, the pattern in observed in-stream nitrate concentrations remains consistent with the other watersheds. The dominant nitrate source in all of these watersheds is associated with wheat production (small grain). The greater Palouse has among the lowest annual precipitation levels in Washington. It may be that the nitrate associated with wheat fertilization not taken up by the crop, or lost through de-nitrification, is largely stored within the upper soil horizon and mobilized once precipitation and associated flows increase during fall and winter.

Annual lows in stream nitrate concentrations coincide with the lowest flows in August and September. However, the lowest nitrate concentrations in the Palouse still remain above the highest concentrations found for the eastern Cascade group. In particular, concentrations remain high for the Walla Walla and SF Palouse suggesting a steady inflow source such as municipal wastewater discharge or the discharge of groundwater with elevated nitrate concentrations.

Eastern Cascade Watersheds

Figures C-15 and C-16 present the monthly median flow and nitrate levels observed for the eastern Cascade watersheds with the relationship between flow and nitrate concentrations observed for the Wenatchee River @ Wenatchee providing a pattern characteristic of this group (Figure C-17). Snow melt is a prominent component of the flow profile April through July accounting for about 78% of the total annual flow volume (Figure C-15). This period coincides with when the lowest nitrate concentrations occur which indicates snow melt’s dilution effect on river concentrations. In contrast to the Palouse, peak nitrate concentrations for the east Cascade watersheds occur September / October when the lowest flows occur. In the case of the Wenatchee this increase is due, in part, to the reduced dilution of point source discharge from several small municipal wastewater treatment plants, in addition to irrigation return flow, and groundwater inflow (Figure C-16). However, nitrate concentrations remain relatively low, particularly in comparison to those observed for the Palouse watersheds. The monthly median nitrate concentrations observed for the Wenatchee River @Leavenworth are significantly lower in comparison to the other monitoring locations for much of the year, with the exception of the period May-June when snow melt has a dominant effect. The Leavenworth monitoring location is situated below Lake Wenatchee and its low concentrations reflect the increased level of nitrate attenuation processes occurring within the lake of up-gradient loading.

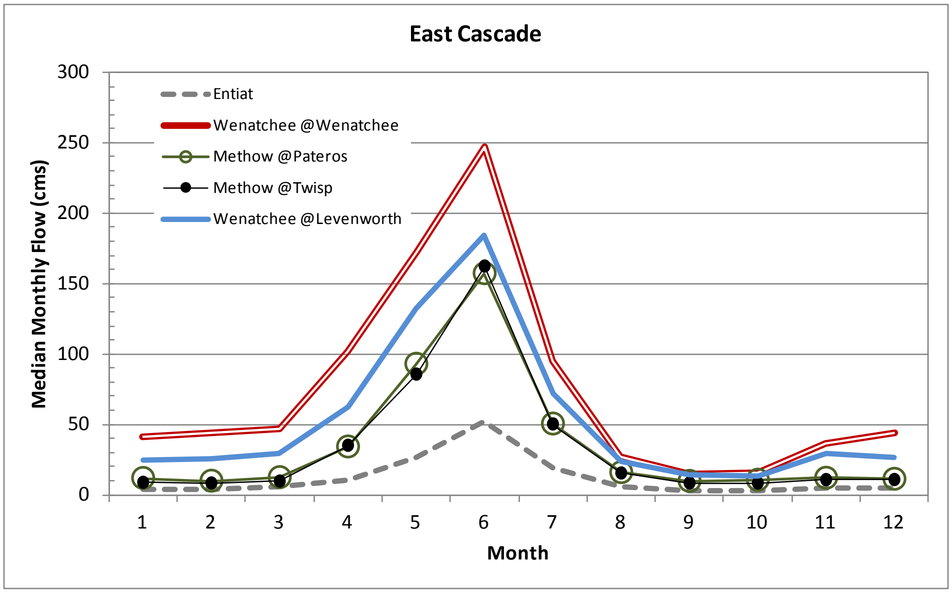


Figure C-15. Median monthly flow variation characteristic of the eastern Cascade watersheds.

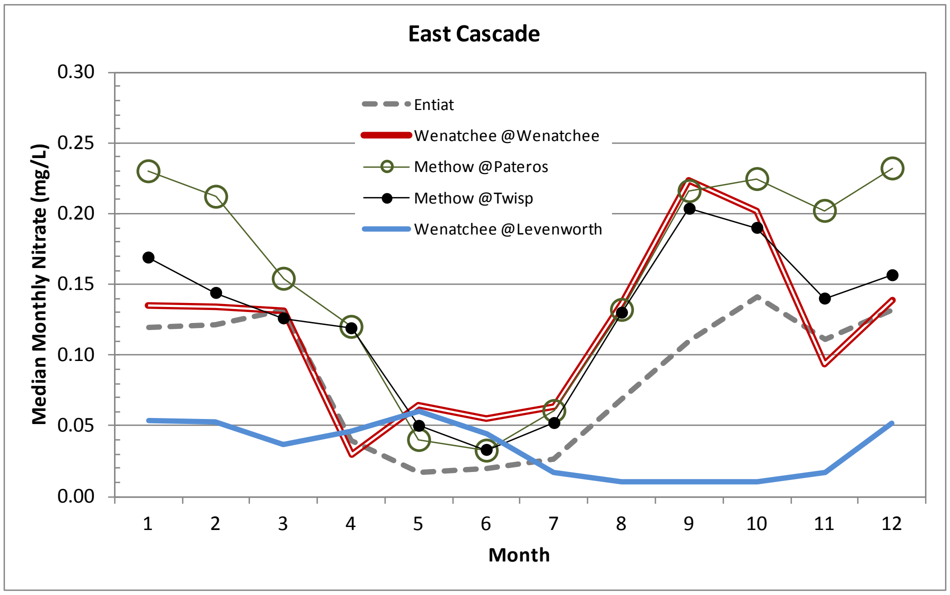


Figure C-16. Median monthly nitrate concentrations characteristic of the eastern Cascade watersheds.

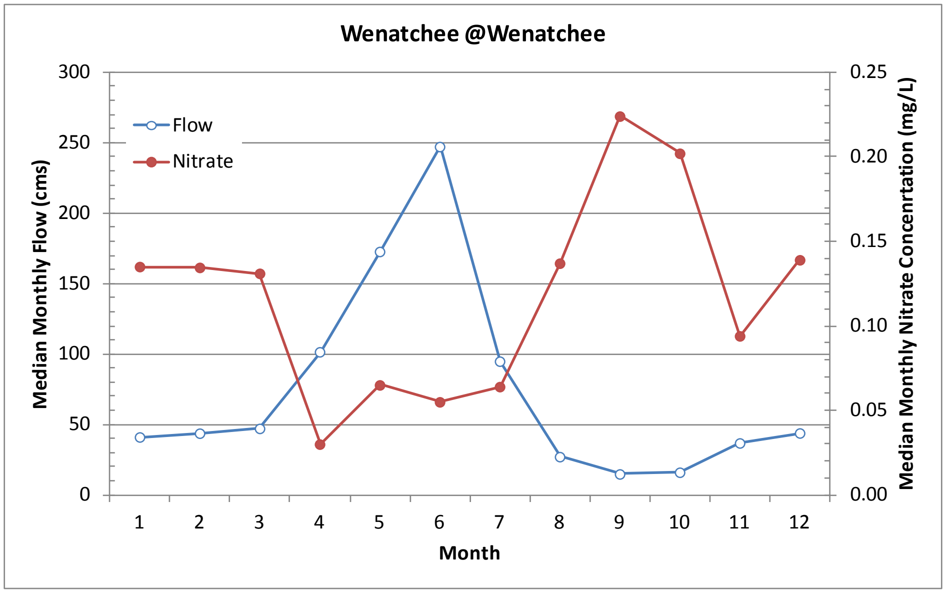


Figure C-17. Monthly nitrate and flow variation: Wenatchee River @Wenatchee.

Yakima River

The Yakima River @Kiona is an example of the relationship between flow and nitrate concentrations in the lower valley (Figure C-18). Flow routing for irrigation, its diversion and return, increases the variability of these relationships throughout the greater Yakima system. Though much of the natural spring snow melt has been captured in upper basin reservoirs, a vestige of that natural flow pattern remains. Flow levels begin to increase in February to a peak in April providing some semblance of spring snow melt but this increase in flow is more the result of reservoir drawdown in order to capture the actual spring snow melt, as the monthly flow variation should be close to that observed for the Wenatchee River which has a flow peak in June, not April. The increase in flow, which is mainly derived from the upper basin, dilutes stream nitrate concentrations since the lowest concentrations are coincident with the flow peak (Figure 20). With declining flow levels, nitrate concentrations increase, May to August, indicating the diminished dilution of point and nonpoint source nitrate loading. The relationship between flow and nitrate levels changes by September when a semblance of a steady state condition is reached. During this time, nitrate concentrations reach an annual peak of about 1.2 mg/L from a low of 0.4 mg/L in April.

In comparison, the median monthly nitrate concentrations observed at the monitoring station Nob Hill are significantly lower in magnitude and seasonal variation. The Nob Hill monitoring station is situated at river mile (RM) 111 about 82 miles upriver of the Kiona station. Nitrate concentrations observed at this monitoring location range between 0.05 mg/L (April) to 0.24 mg/L (February). The range in the seasonal nitrate variation for Kiona is 0.40 mg/L (April) to 1.24 mg/L (November). Apparent from Figure C-18 is that the differences in the magnitude of flow and its seasonal variation between these two monitoring locations reflect the complexity of flow management in the lower Yakima watershed. And, in turn, that management combined with the more intensive nitrate-generating activities situated in the lower Yakima valley result in the increased concentrations observed.

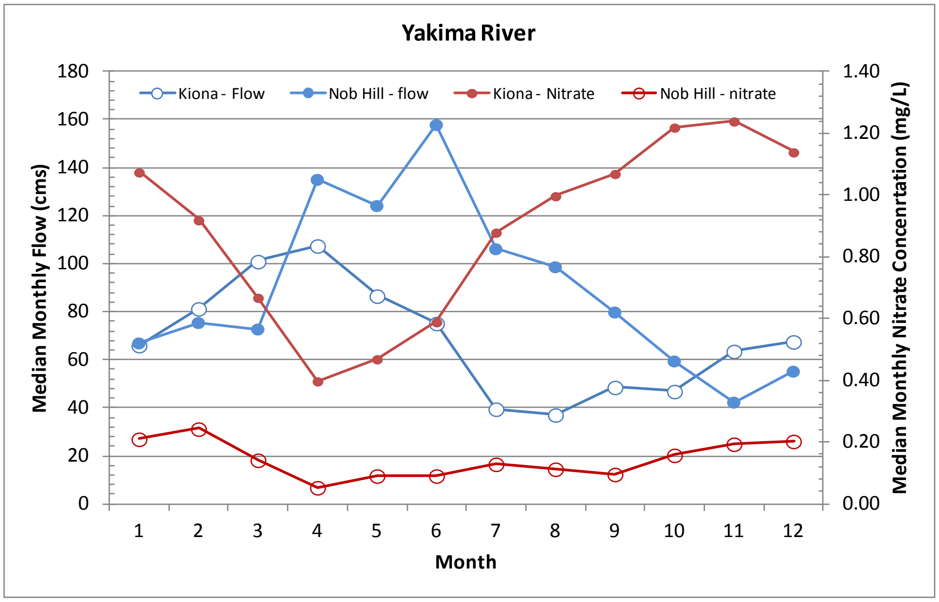


Figure C-18. Monthly median flow and nitrate levels for Yakima River monitoring locations Kiona and Nob Hill.

Spokane River

The monthly variation of flow and nitrate concentrations observed for the Spokane River @Riverside (Figure C-19) are close to that found for the Wenatchee River @Wenatchee (refer to Figure C-17). There are many similarities between the river systems. In terms of hydrology, lakes form the headwaters of both systems and snow melt is prominent in their annual flow pattern. There are differences in the timing to the snow melt peak: the Wenatchee peak in June while for the Spokane it is May. But snow melt has the same effect in both rivers serving to dilute typical nitrate river concentrations. Higher flows result in lower nitrate concentrations indicating that the dominant loading pathway is not overland flow. A characteristic of the variation in nitrate concentrations indicative of point source dominated drainages is that the annual maximum concentrations occur at base-flow when dilution is at a minimum. The largest source of nitrate to the Spokane River, above the monitoring location, is the city’s municipal wastewater treatment plant (WWTP), which provides a relatively steady monthly nitrate load to the river. Alternatively, this also is the pattern for drainages with elevated groundwater nitrate concentrations. Groundwater inflow, relative to other flow sources, is also at an annual peak at base-flow.

At the peak flow in May, nitrate concentrations are reduced through dilution, to 0.2 mg/L. At the low flows in August / September the dilution effect is gone and nitrate concentrations are at an annual peak of about 1.2 mg/L. As will be discussed later in this report, groundwater has an important role in the hydrology of the Spokane and it major tributary the Little Spokane River, affecting nitrate loading and concentrations. From Figure C-19, the monthly median flow levels are very similar between the Spokane River at Stateline (RM 96) and Riverside (RM 66). Much of the flow observed at the Stateline monitoring location migrates between surface and subsurface flow but the majority is eventually discharged, by either pathway, to the Riverside reach. While flow levels are similar between the two monitoring locations there are significant differences in the monthly median nitrate concentrations, primarily the result of WWTP discharge.

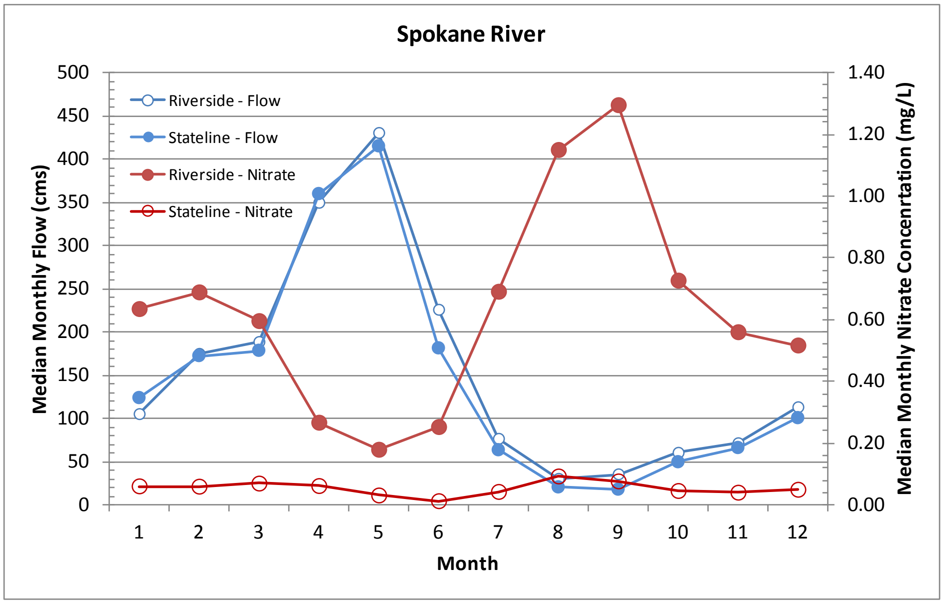


Figure C-19. Spokane River @Riverside Park, an example of a point source and snow-melt-type response to flow and nitrate monthly variation.

Crab Creek

Crab Creek is among the largest watersheds in Washington and perhaps the most complex hydraulically because it is central to the massive Columbia Basin Project irrigation scheme. The source of water for irrigation is the Columbia River. The Yakima River, also managed for irrigation, differs from Crab Creek in that its source of water lies entirely within its watershed. So while the timing, routing, and distribution of water has changed for the Yakima River, the overall water yield is comparable to what existed prior to flow management. In contrast, water for the Columbia Basin Project originates from the Columbia River outside of the Crab Creek watershed. It is entirely imported. While Crab Creek continues to have among the lowest water yields of the watersheds considered by this study it is above what occurred prior to the Project. Channels comprising the watershed network were likely dry for much of the year similar to those currently situated outside of the current irrigation scheme. In considering the flow and nitrate levels observed at Crab Creek @Beverley there are two periods: the main irrigation-influenced period, from May to August, and the rest of the year (Figure C-20).

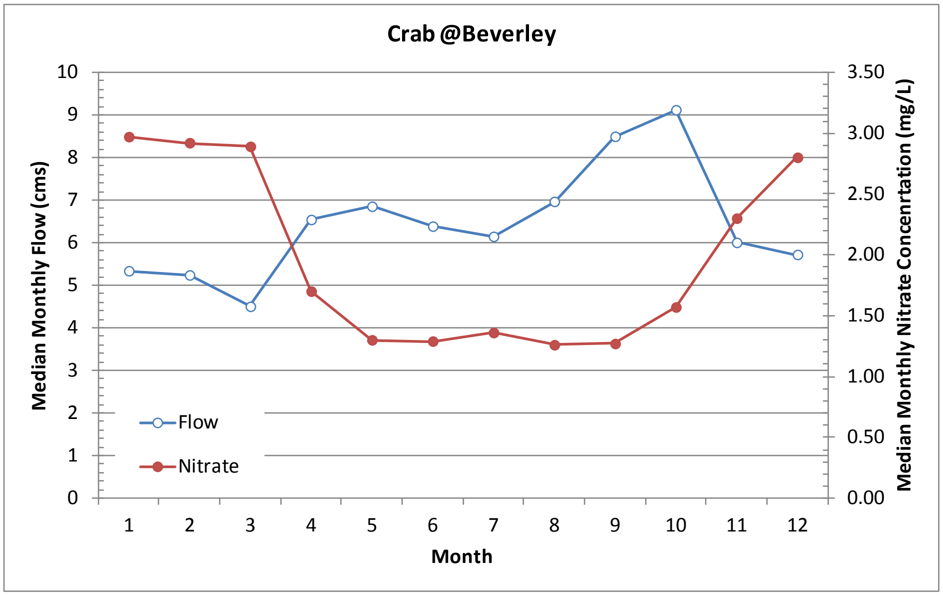
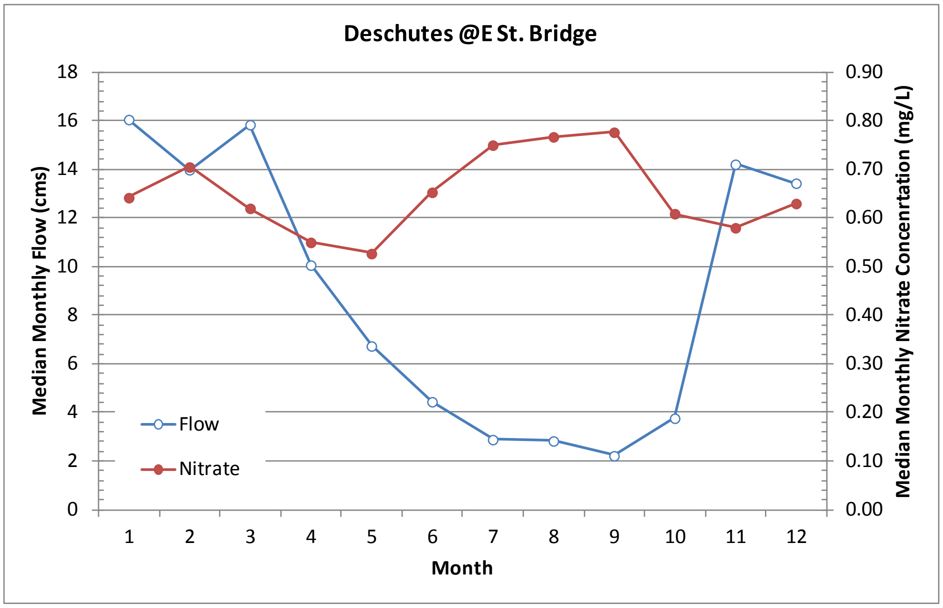


Figure C-20. Monthly flow and nitrate levels observed at the Crab Creek @Beverley monitoring station.

Outside of the irrigation season, January to April and September to December, there is a significant inverse relationship between flow and nitrate: as flows increase, nitrate concentrations decline. At the lowest flows, which occur from December to March at around 5 cubic meters per second (cms), nitrate levels reach a peak concentration of around 3 mg/L. This relationship indicates a dilution effect is occurring associated with the irrigation inflow. It is important to note that in comparison to most of the other study watersheds the flows and nitrate levels for Crab Creek, while elevated, have relatively low variability. The monthly median flows have a range of between about 5 cubic meters per second (cms) in March to 9 cms in October. The peak nitrate concentrations are 3 mg/L lowering to about 1.5 mg/L during the irrigation season. The elevated base nitrate level and the inverse relationship between flows and nitrate levels suggests that the nitrate introduced up-gradient of the monitoring station emanates from a form of storage such as a reservoir and (or) groundwater discharge.

Alternative watersheds: Samish, Deschutes, Little Spokane River

Deviation from the typical flow/nitrate seasonal variations characteristic of the various groups presented provides insight into alternative nitrate loading pathways. Several of the study watersheds share a similar dynamic between flow levels and nitrate concentrations as Crab Creek including the Little Spokane River, and the Deschutes and Samish Rivers in western Washington (Figures C-21 and C-22). This is a diverse assemblage of drainages but all share the characteristic of a fairly constant nitrate concentration through varying flow levels with the maintenance, or increase in concentration, occurring at base flow. There's no significant correlation between flow and nitrate levels. The reason for this is that the groundwater in these watersheds has elevated nitrate levels, prominently expressed at base flow. These stations have all been placed into a common group referred to as groundwater. The Samish and Deschutes River watersheds would normally be grouped with western Washington's low elevation watersheds since both have less than 5% of their drainage above 1,000 meters. And, while the monthly flow variation for these watersheds is consistent with low elevation drainages, the variation in nitrate is not. In both cases, there is a source of nitrate that maintains or elevates (Deschutes) concentrations as flows decline. Typically, for the low elevation groups, the lowest nitrate concentrations are present at base flow in August / September when groundwater discharge provides that greatest source of stream flow. However, it appears that for the Deschutes and Samish Rivers that groundwater with more elevated concentrations of nitrate is the reason why there is the maintenance or increasing concentrations at base flow.



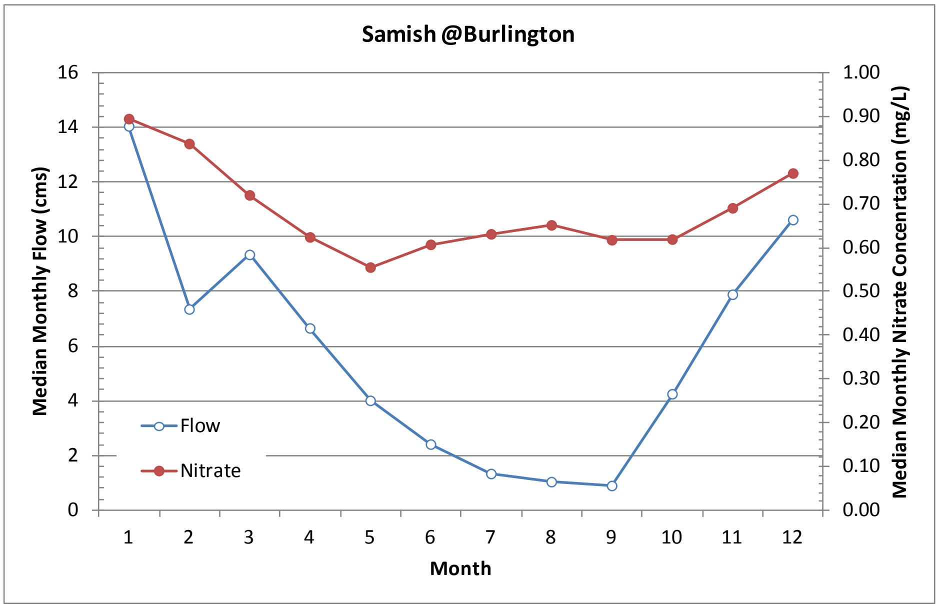


Figure C-21. Median monthly flow and nitrate levels for the Deschutes and Samish River monitoring locations.

The Little Spokane River is a more complex situation but fundamentally the same as the Deschutes and Samish Rivers. Flow from the Spokane Valley Rathdrum Prairie Aquifer discharges to the Little Spokane River at an approximate annual average rate of 7 m^3/s and a nitrate concentration of 1.4 mg/L; comprising about 64% of the annual load. This load is delivered at a relatively constant level throughout the year as opposed to land-based sources where loading is more typically associated with the level of overland flow. Therefore, the relative average annual concentrations for overland flow-based drainages are heavily weighted to when the highest flows occur as opposed to groundwater-based loading that is more evenly distributed. Complicating the situation for the Little Spokane River is a period of spring snow melt that dilutes loading associated with overland and groundwater-based inflow. As flows decline to base levels by July, when groundwater discharge is comprised of both that derived within the watershed and that imported from the Rathdrum Aquifer, nitrate concentrations increase to peak levels of around 1.2 mg/L (Figure C-22).

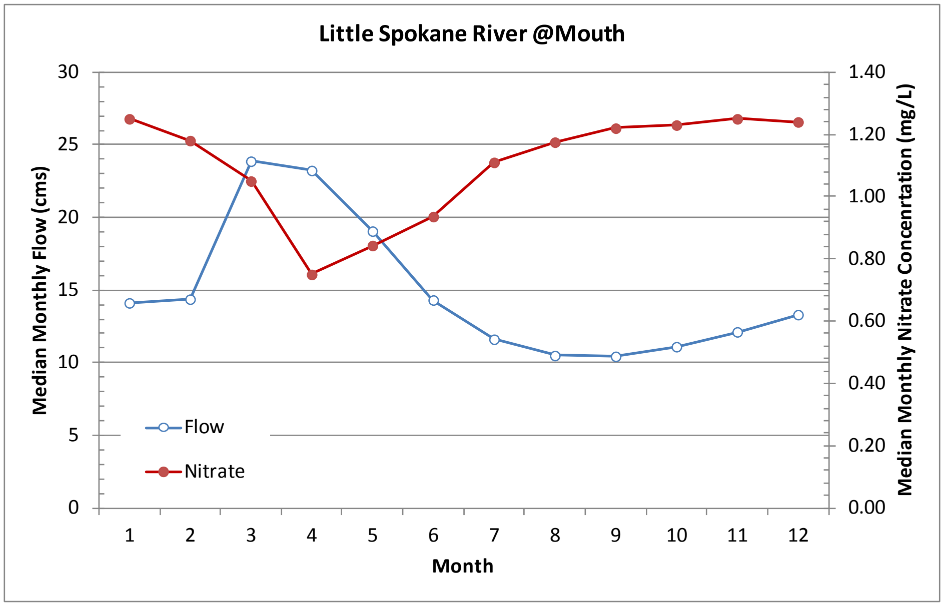


Figure C-22. Median monthly flow and nitrate levels for the Little Spokane River @mouth.

These watersheds demonstrate that they cannot all be easily categorized. While more easily identified, the managed watersheds, whether for hydroelectric power generation or irrigation, comprise a substantial portion of the state and require an individual assessment. A watershed's soils and underlying geological characteristics are significant factors in affecting the vulnerability of groundwater to nitrate loading which is why the variation in nitrate for the Deschutes and Samish differs from that of other low elevation watersheds.

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Appendix D. Flow, Nitrate Concentrations and Yields

Annual and monthly flow estimates

Despite location and seasonal differences in the timing and magnitude of flow among the study watersheds they share a common relationship between their annual average precipitation level (presented in units of meters per year - m/yr.) and the annual runoff volume (cubic meters of runoff per square meter of receiving area per year – m^3/m^2-yr or m/yr.) (Figure D-1, Table D-1). The data are segregated by location, eastern or western Washington watersheds, but the power relationship presented is based on the combined data.

From Figure D-1 and Table D-1 with an understanding of the average annual precipitation and drainage area, an estimate of the median monthly flow for the various watershed groups (non-managed) can be derived. These relationships will be examined further in assessing the application of the nitrate exports coefficients, presented earlier in this report, as a means to ultimately estimate median monthly nitrate concentrations.

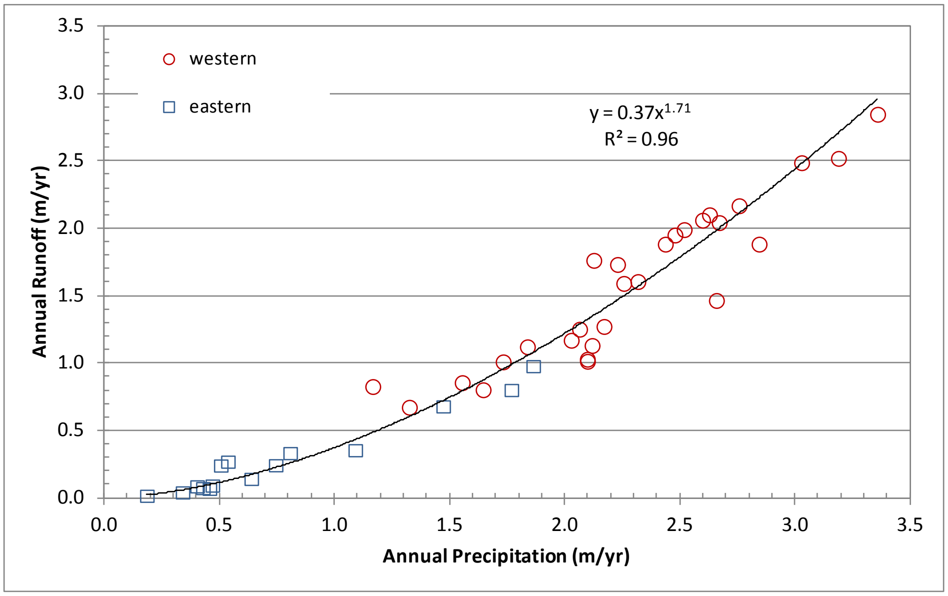

Figure D-1. The relationship between annual average precipitation and average net runoff for the study watersheds.

Table D-1. Percent of the total average annual surface water outflow occurring monthly.

Flow Group	Percent of median annual discharge occurring monthly (%)											
	1	2	3	4	5	6	7	8	9	10	11	12
Mid- Elevation	15.0	10.5	12.8	10.5	8.5	5.5	2.8	2.0	2.2	4.7	12.2	12.7
High-Elevation	10.7	7.2	9.3	10.2	13.5	10.5	5.1	2.5	2.6	6.7	10.3	8.8
Low-Elevation	14.5	13.9	14.5	8.3	3.8	2.4	1.2	0.8	0.8	5.8	16.9	16.4
East Cascades	2.8	3.0	4.0	8.5	20.7	36.6	11.8	3.7	2.2	2.0	3.1	3.3
Yakima	6.9	7.5	10.0	12.8	11.1	10.6	8.5	8.3	6.9	5.6	6.1	6.9
Spokane	5.3	7.8	10.3	20.4	23.4	12.3	3.9	1.4	1.8	2.8	3.8	5.9
Palouse	9.8	18.3	25.6	18.3	9.9	6.6	1.2	0.6	0.5	0.9	2.1	5.0
Crab	6.9	6.8	5.8	8.5	8.9	8.3	8.0	9.0	11.0	11.8	7.8	7.4

Nitrate concentrations and yields

The percent of the annual nitrate yield (kg/km^2-yr) occurring monthly for the western and eastern Washington flow groups are presented in Figures D-2 and D-3 and Table D-2.

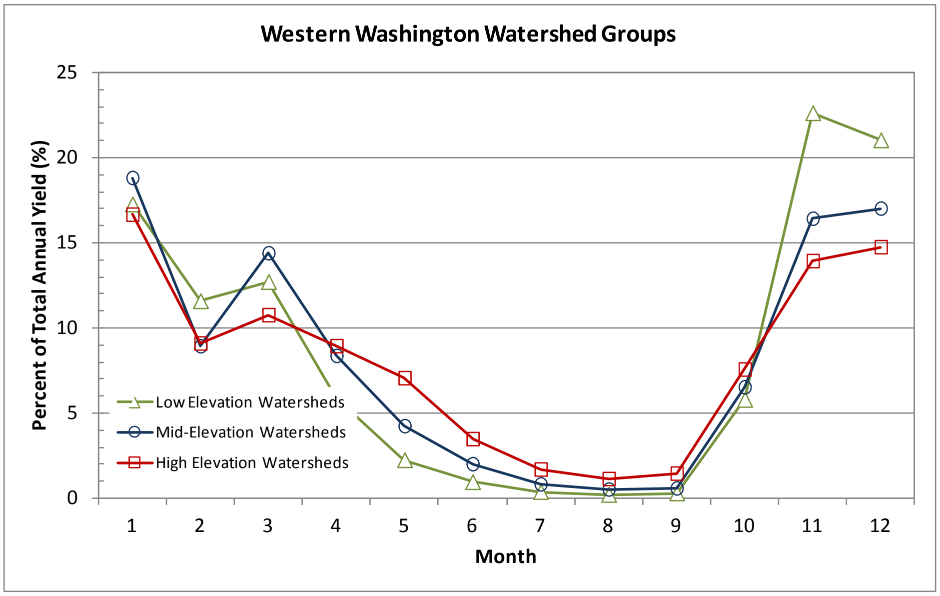

Figure D-2. Percent of the total annual nitrate yield occurring monthly for the western Washington drainage groups.

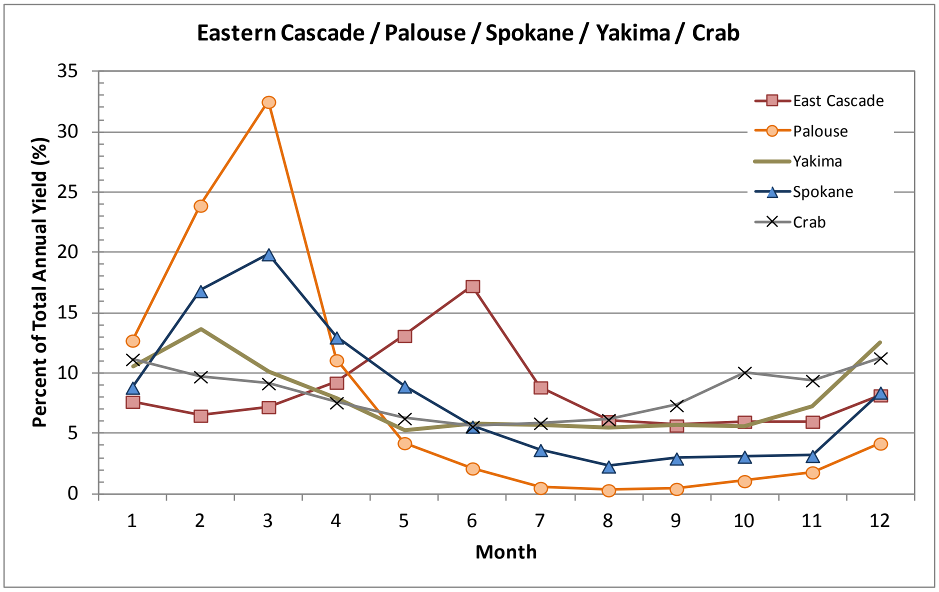

Figure D-3. Percent of the total annual nitrate yield occurring each month for the eastside drainage groups.

Table D-2. Percent of the median annual nitrate yield occurring monthly, by flow group.

Flow Group	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Mid-Elevation	18.2	11.5	13.0	8.1	4.2	2.4	1.2	1.0	1.1	3.5	14.7	17.4
High Elevation	16.9	9.1	10.8	9.4	7.6	4.2	2.1	1.6	1.6	6.3	13.5	14.1
Low Elevation	17.5	13.1	13.5	5.6	1.6	0.9	0.4	0.2	0.2	2.6	22.0	21.0
East Cascades	7.5	5.6	5.7	10.8	15.2	18.4	8.7	5.9	5.6	5.6	5.1	7.7
Yakima	10.7	10.2	10.2	5.2	6.4	6.5	6.4	6.9	5.6	7.0	10.0	11.6
Spokane	6.9	8.8	14.8	31.4	12.3	4.2	2.7	1.6	1.1	1.9	2.3	6.8
Palouse	11.3	23.9	33.2	13.3	4.6	1.5	0.3	0.1	0.1	0.3	0.7	4.2
Crab	11.1	10.5	9.0	7.8	6.1	5.6	5.5	6.3	7.5	9.8	9.5	11.5

The relationship between the annual nitrate yield and annual flow-weighted concentration for eastern and western Washington drainages is presented in Figure D-4. While recognizing the variability present, the figure illustrates the overall rate of increasing nitrate concentrations with increased yields and that nitrate concentrations observed in eastern Washington watersheds are considerably higher, over similar ranges in yields, in comparison to those determined for western Washington watersheds. There is approximately an order of magnitude increase in the annual average nitrate concentration for eastern drainages in comparison to those in western Washington. Lower water yields for eastern drainages reduce the level of dilution for comparable nitrate loading levels. This factor results in a greater vulnerability of the eastern drainages to point and nonpoint source loading, elevating nitrate concentrations in both surface and groundwater.

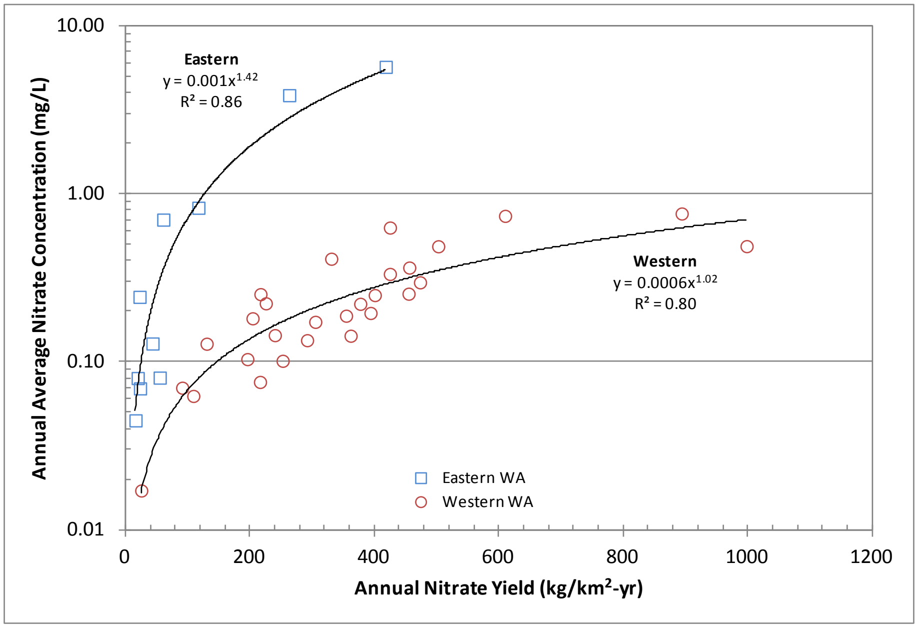

Figure D-4. The relationship between the annual nitrate yield and the annual flow-weighted average concentration for western and eastern Washington drainages.

The level of storage, primarily in the form of reservoirs, is an important factor affecting the variability of these relationships. Western Washington watersheds with reservoir storage include: Cedar, Cowlitz, Elwha, Green, Nisqually, Puyallup, Skagit, and the Skokomish. Study watersheds with storage in eastern Washington include: Crab, Wenatchee, Spokane, and the Yakima. As it was discussed earlier in this report, only the drainage area situated below reservoirs or, in some cases, lakes, provide significant contributions to observed nitrate loading. This is because in-line reservoirs and lakes provide a net sink (attenuation) to the up-gradient nitrate loading due to various physical, chemical, and biological processes that occur within them. The effective area is defined by the catchment area down-gradient of the reservoir that significantly contributes to the loading observed at the watershed outlet. For drainages with reservoirs, the yields presented in Figure D-4 are based on their effective area.

Despite accounting for effective area, watersheds with reservoir storage produce lower average annual concentrations in comparison to those without. This is because nitrate concentrations in reservoir discharge tend to be low, often at the level of detection, diluting the effects of downstream nitrate loading in comparison to watersheds without storage.

Watershed location differences among the watersheds are reduced when the annual average nitrate concentrations are compared to the average occurring during base-flow (Figure D-5). The flow and nitrate levels observed during August and September are assumed to represent the base-flow condition. Base-flow nitrate concentrations provide an indicator of the overall average groundwater concentration throughout the drainage since the influence of overland flow is at an annual minimum. Potentially, based on the type and intensity of overlying land use activities, there could be localized areas of highly contaminated groundwater though its impact greatly diluted by a relatively un-impacted upper drainage area. That is why the base flow nitrate concentration provides an indicator of watershed-wide average groundwater nitrate concentrations, not site-specific impacts. In addition, the data considered does, in some cases, include point source loading from wastewater treatment plant discharge though that effect has been minimized by eliminating drainages with higher point source discharge levels from this comparison (i.e. Spokane River @Riverside, Palouse @Palouse). The western and eastern drainages are plotted separately but the relationship that is presented considers the entire dataset due to their similar response. The previous relationship (Figure D-4) indicated that the greater the net nitrate loading yield the greater the average annual concentration with higher concentrations occurring for eastern drainages in comparison to western drainages due to differences in hydrology. Figure D-5 finds more commonality between the western and eastern drainages. The base-flow nitrate concentrations increase with increasing annual average concentrations which, in turn, are both determined by the level of nitrate loading occurring within the drainage. Higher intensities of nitrate loading, expressed as a yield, lead not only to the expected higher average surface water concentrations but also higher base flow concentrations, an expression of groundwater.

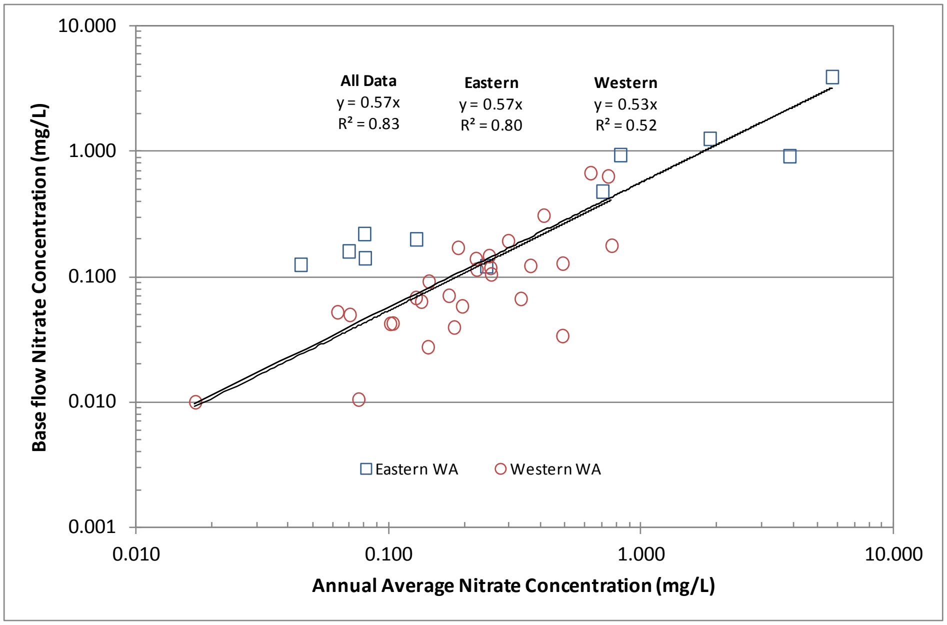

Figure D-5. The relationship between the annual average nitrate concentration and those observed at base flow for the eastern and western Washington watersheds.

The background nitrate condition

Figure D-6 presents the application of the monthly flow and loading percentages (Tables D-1 and 2) to the Chehalis River @Dryad, a low elevation type watershed. The drainage area estimate of annual precipitation was 2.1 meters which when applied to the relationship in Figure D-1 results in a net runoff yield of 1.32 m/yr. (The observed runoff yield was 1.03 m/yr, 22% less overall than estimated.) The annual net nitrate yield observed at the Chehalis monitoring station was 484 kg/km^2-yr, about twice the estimated background level of 266 kg/km^2-yr for western Washington. Median monthly nitrate concentrations, representative of the background condition, were estimated based on monthly load distribution of the net background yield of 266 kg/km^2-yr divided by the corresponding estimated monthly flows. Comparison between the current to background concentrations indicates about an 80% decrease occurs November to February coinciding to when the greatest flows occur. This is a period of peak concentrations and flows but the estimated background nitrate concentrations are about 0.3 mg/L while the current concentrations over the same period are about twice that level at 0.6 mg/L. As a comparison, the observed median monthly nitrate concentrations for the Humptulips are also included in Figure D-6. The Humptulips River provides a good representation of background conditions for nitrate loading in western Washington due to the high representation of land use in evergreen-type forest. And, as observed, the median monthly nitrate concentrations observed for the Humptulips are close to that predicted for the Chehalis at the assumed background loading yield.

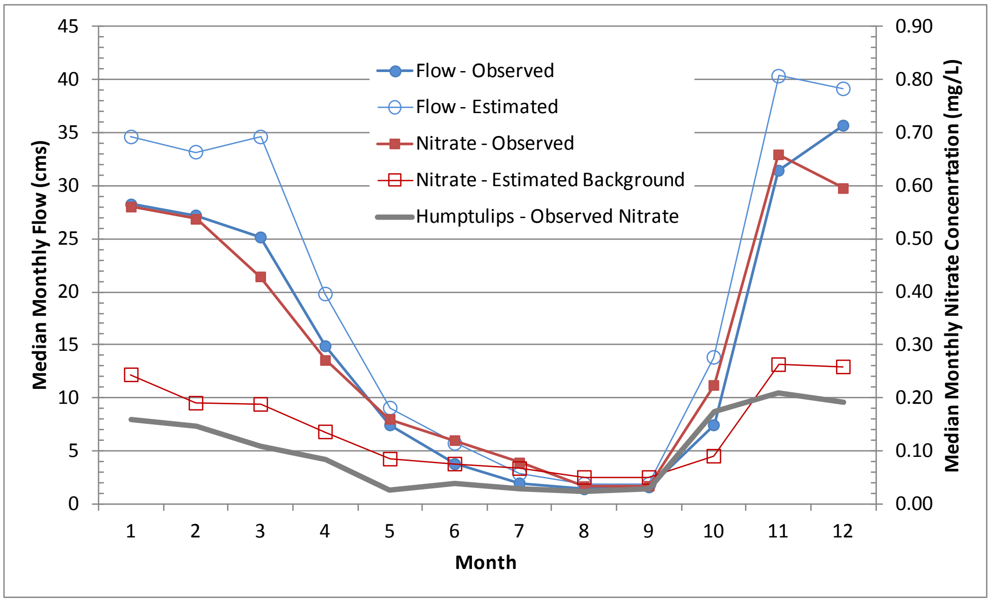

Figure D-6. Observed (current) and estimated background nitrate concentrations for the Chehalis River @Dryad monitoring location.

Appendix E. Nitrate loading in the Nooksack, Sumas, and Crab Creek Watersheds

Nooksack River

The Nooksack watershed hydrologic unit code (HUC) areas and their position in the overall watershed flow network are provided in Figures E-1 and E-2, respectively. Also included in the figures and analysis is the relatively small Sumas River drainage which flows north, away from the Nooksack watershed, into British Columbia, Canada. It is included in this analysis because the Sumas shares common land uses as those found for the lower Nooksack valley.

Overview of Land Use

The majority of the study area is heavily forested and mountainous. The Upper North Fork and Middle Fork Nooksack HUCs, in particular, have about 80% forest land coverage and 6-8% as perennial ice and 4-7% bare rock (Table E-1). Each could be considered a background condition from a nitrate loading perspective. Both HUCs include portions of the 3,300 meter Mount Baker. The South Fork is transitional having the Twin Sisters Mountain (2,000 meter) and forest land cover in its upper drainage and the beginning of the lower Nooksack valley at its outlet where agricultural farm land is situated. Forest lands comprise about 80% of the drainage area. The lower elevations present in the South Fork in comparison to the Upper North Fork and Middle Fork is indicated by the increased presence of deciduous tree cover at about 12% of the drainage area and pasture (3%). The Lower North Fork furthers the mountains to valley transition with about 80% in forest land and 18% in deciduous cover with pasture comprising about 2% of the drainage. The Lower North Fork and South Fork are fairly similar in generalized land use descriptions.

The valley is reached by the Sumas and Nooksack River – Frontal HUCs, both locations of extensive agricultural production, primarily dairy. The forest land cover is significantly lower at between 20% (Nooksack-Frontal) to 37% (Sumas) and pasture land has a significantly higher presence at 33% (Sumas) to 42% (Nooksack-Frontal). Row crops (berries) comprise about 12% of the Sumas HUC. Populations are low in the Middle and Upper North Fork, at less than 1,000 (Table E-2). The lower North Fork and South Fork also have similar populations at around 3,000. The population center is the Nooksack-Frontal HUC with 88% of the watershed total of 65,302. The population of the Sumas HUC is about 7,500. Given the population disparity, WWTP discharge is largely limited to the Nooksack-Frontal, with an annual surface water discharge level of 4,439,047 cubic meters. The Nooksack and Sumas HUCs are located in Whatcom County, a center of the dairy industry in western Washington. The estimated dairy cow population for the Nooksack-Frontal and Sumas HUCs are about 32,000 and 16,000, respectively.

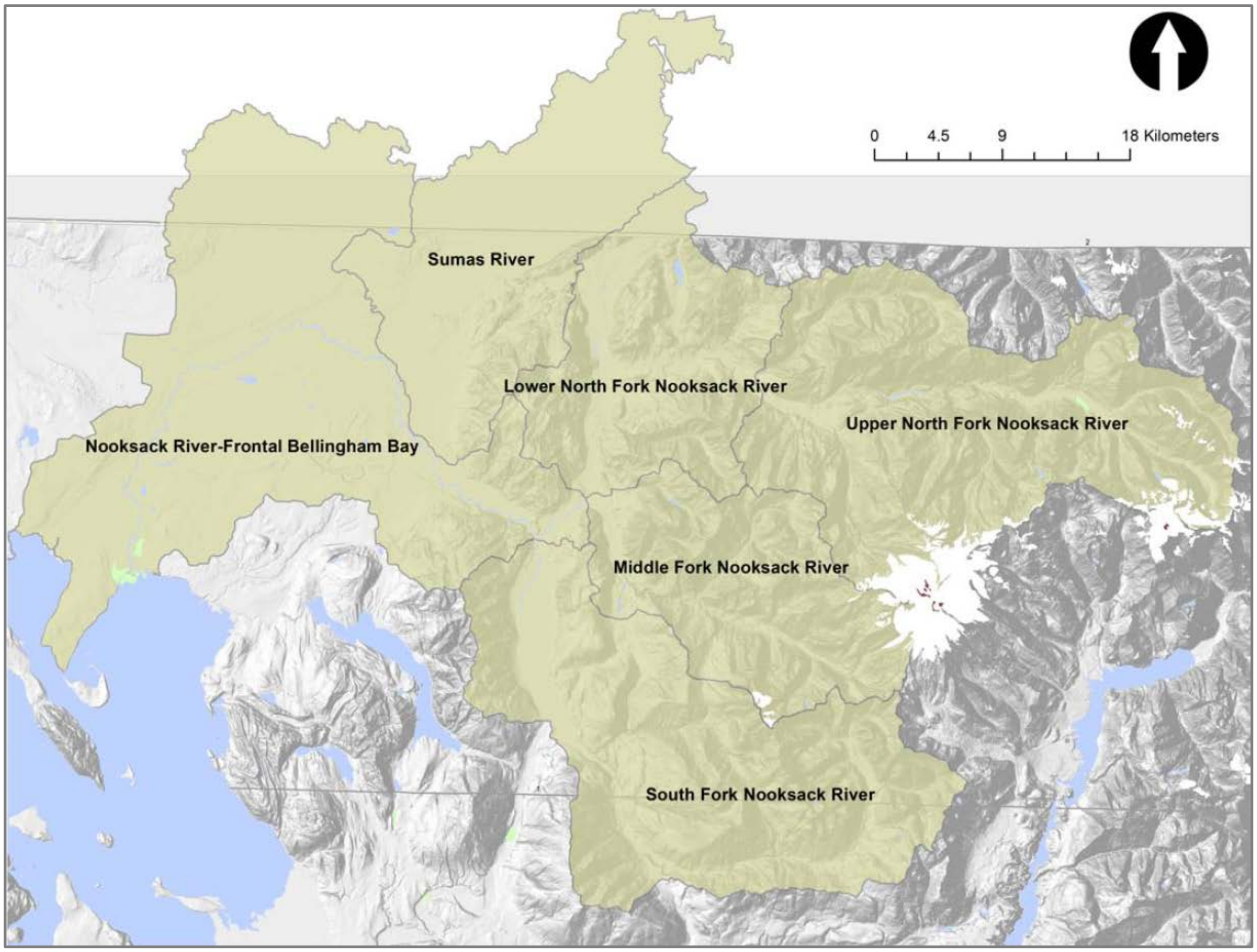

Figure E-1. The HUCs comprising the Nooksack and Sumas watersheds.

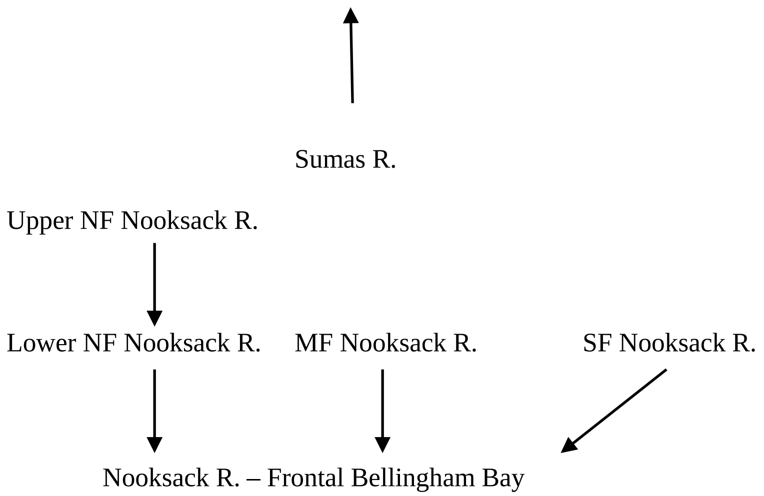

Figure E-2. Flow Schematic for the Nooksack and Sumas watersheds based on the USGS HUC-10 delineation.

Table E-1. Percent representation of NLCD land uses within the Nooksack and Sumas watersheds, by HUC.

HUC Name and No.	Area (km^2)	Open Water	Perennial Ice / Snow	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Lower NF Nooksack 1711000402	261	1.0	===	0.8	0.2	76.6	17.9	2.3	0.4	===	0.1	0.2
MF Nooksack 1711000403	257	0.4	6.3	===	4.4	80.1	6.2	0.1	2.3	===	===	===
Nooksack – Frontal Bellingham Bay 1711000405	668	1.3	===	4.2	0.2	22.3	21.9	41.5	0.9	1.0	1.6	4.2
SF Nooksack 1711000404	481	0.5	0.6	0.1	2.5	78.9	11.9	3.1	1.8	0.3	===	0.2
Upper NF Nooksack 1711000401	500	0.4	8.7	===	7.2	76.0	3.6	===	4.1	===	===	===
Sumas 1711000104	150*	===	===	1.3	===	36.6	12.7	32.8	0.9	1.0	2.0	12.4

*Reflects just the portion of the drainage monitored in Washington.

Table E-2. The nitrate loading attributes for the Nooksack and Sumas watersheds.

HUC Name	Population (No.)	Municipal Surface Discharge (m^3/yr)	Municipal Land Discharge (m^3/yr)	Dairy Cows (No.)	Beef Cows (No.)
Lower NF Nooksack	3,351	===	72,635	===	1,861
MF Nooksack	695	===	===	===	1,937
Nooksack – Frontal Bellingham	57,757	4,439,047	===	31,987	4,091
SF Nooksack	2,985	===	===	1,315	3,048
Upper NF Nooksack	514	===	===	===	3,753
Nooksack Watershed	**65,302**	**4,439,047**	**72,635**	**33,302**	**14,690**
Sumas	7,499	===	===	15,774	1,351

Results

Loading to land surface / groundwater

The greatest net land-based nitrate yields occur in the Nooksack River – Frontal Bellingham Bay and Sumas HUCs at 900 kg/km^2-yr and 1,446 kg/km^2-yr, respectively (Figure E-3). The effect of these loading yields on the underlying groundwater was presented previously in Figure 19. They are among the highest groundwater nitrate levels observed for western Washington and are primarily related to hay/pasture and dairy production (Tables E-3 and E-4). The nitrate loading estimates for the Nooksack-Frontal and Sumas HUCs assumed that pasture fertilization is entirely derived from the spread of dairy waste, given the high number of dairies present in both HUCs. This assumption negates the possibility of "double counting" dairy-related nitrate loading.

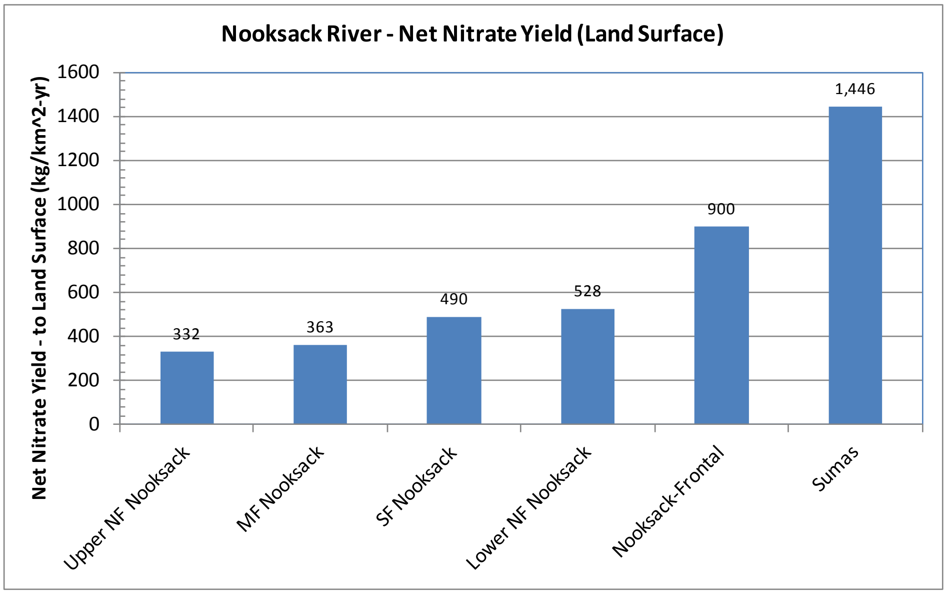

Figure E-3. Net land-based nitrate yields, by HUC, estimated for the Nooksack and Sumas watersheds.

In the Nooksack River – Frontal, dairy production comprises 36% of the total annual net land-based load while in the Sumas the level is 49% (Table E-4). It is rare that a HUC or watershed in western Washington has such an overwhelming single nitrate source. More common are multiple sources at more equivalent levels of representation. However, excluding forestry / shrub land cover, which are considered background, the eastern Washington drainages tend to have a higher representation of single or dominant land use types and activities compared to the more varied and lower representation of land use types typically found in western Washington. Expansive urbanization characterizes the Interstate-5 corridor in western Washington though its net nitrate export level of 800 kg/km^2-yr, by extrapolation, relates to an average groundwater concentration of about 3 mg/L. This leads to a lower potential for nitrate contamination of groundwater (exceeding 10 mg/L) for all but the most intensive source areas such as the high densities of dairies in Whatcom County (Sumas, Nooksack-Frontal HUCs). These high yields occur despite the assumed net loss of dissolved inorganic N associated with dairy waste of 96%. The only other significant nitrate source for these two HUCs is associated with berry production which is estimated to contribute about 19% and 11% of the annual total in the Sumas and Nooksack-Frontal HUCs, respectively.

Table E-3. The estimated net annual nitrate load (kg) applied to the land surface within each of the Nooksack River and Sumas HUCs.

HUC Name	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Land-Based Municipal Wastewater	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain	Row Crop (berries)
Low. NF Nooksack	1,466	90	53,055	46,773	1,453	5,931	===	16,083	10,725	258	93	186	928
MF Nooksack	72	2,791	54,621	15,839	===	1,461	===	16,732	301	1,567	2	6	14
Nooksack – Frontal	20,190	124	39,514	145,866	===	53,739	216,232	35,334	*	1,545	12,583	10,825	63,334
SF Nooksack	412	2,367	100,443	56,957	===	6,268	8,886	26,332	26,587	2,310	2,460	145	2,243
Up. NF Nooksack	74	8,737	100,668	17,812	===	1,079	===	32,426	===	5,387	===	1	===
Nooksack Watershed	**22,213**	**14,111**	**348,301**	**283,247**	**1,453**	**68,478**	**225,119**	**126,916**	**37,613**	**11,066**	**15,138**	**11,266**	**66,497**
Sumas	1,424	===	14,540	19,102	===	15,748	106,635	11,673	*	345	2,778	3,030	41,576

- Pasture load assumed a component of dairy production

The net nitrate yield estimated for the Upper North Fork (332 kg/km^2-yr) and Middle Fork (363 kg/km^2-yr) HUCs are characteristic of a background loading condition. The 46% increase in yield for the Lower North Fork and South Fork in comparison to the Upper North Fork and Middle Fork is associated with the decrease in forest land cover (-19% of annual load), and increase in deciduous cover (+15%), on-site systems (+3%), and pasture lands (+10%). Still, these HUCs remain at a relatively low yield compared to those of the Nooksack-Frontal and Sumas HUCs.

Loading to surface water

The difference between the land-based yield and the surface water yield is due to an accounting of effective area and the direct discharge of municipal wastewater. There is also the consideration of loss pathways, such as through precipitation storage as ice and attenuation within lakes, when reservoir storage is not present. Since there is not significant storage within the Nooksack or Sumas HUCs, effective area is not a factor. There is loss associated with storage as perennial ice for the Upper North Fork and Middle Fork Nooksack HUCs. The only municipal wastewater discharge occurs in the Nooksack-Frontal HUC from the Everson, Ferndale, and Lynden WWTPs. But their combined discharge comprises only about 6% of the total annual load, considering the other sources. For these reasons, the land-based and surface water yields are similar (Tables E-5 and E-6).

Table E-4. The percent representation of the net annual load to land surface, by land use, for the Nooksack and Sumas HUCs

HUC Name	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Land-Based Municipal Wastewater	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Lower NF Nooksack	1.1	0.1	38.4	33.9	1.1	4.3	===	11.7	7.8	0.2	0.1	0.1	0.7
MF Nooksack	0.1	3.0	58.5	17.0	===	1.6	===	17.9	0.3	1.7	===	===	===
Nooksack – Frontal	3.4	===	6.6	24.3	===	8.9	36.0	5.9	*	0.2	2.1	1.8	10.5
SF Nooksack	0.2	1.0	42.6	24.2	===	2.7	3.8	11.2	11.3	1.0	1.0	0.1	1.0
Upper NF Nooksack	===	5.3	60.6	10.7	===	0.6	===	19.5	===	3.3	===	===	===
Nooksack Watershed	**1.8**	**1.1**	**28.2**	**23.0**	**===**	**5.5**	**18.2**	**10.3**	**3.0**	**0.9**	**1.2**	**0.9**	**5.4**
Sumas	0.7	===	6.7	8.8	===	7.3	49.2	5.4	*	0.2	1.3	1.4	19.2

*Assumed majority of pasture fertilized with dairy waste

Table E-5. Estimated net annual nitrate loading to surface water and land surface for the Nooksack and Sumas HUCs

HUC Name	Drainage Area (km^2)	Net Nitrate Load and Yield to Land Surface		Net Nitrate Load and Yield to Surface Water	
		kg/yr	kg/km^2-yr	kg/yr	kg/km^2-yr
Lower NF Nooksack	261	137,991	528	125,041	479
MF Nooksack	257	93,419	363	73,439	285
Nooksack – Frontal Bellingham	668	600,925	900	646,387	968
SF Nooksack	481	235,548	490	221,839	462
Upper NF Nooksack	500	166,225	332	114,862	230
Nooksack Watershed	**2,167**	**1,234,046**	**570**	**1,181,563**	**545**
Sumas	150*	216,861	1,446	216,763	1,445

*Reflects drainage area situated within Washington

Table E-6. The cumulative annual nitrate loading to surface water and land surface for the Nooksack and Sumas watersheds, by HUC.

3° Tributary	2° Tributary	1° Tributary	Nooksack Main-stem	Net Cumulative Nitrate Load and Yield			
				Surface Water		Land Surface	
				Load (kg/yr)	Yield (kg/km^2-yr)	Load (kg/yr)	Yield (kg/km^2-yr)
	Upper NF Nooksack 1711000401			114,862	230	166,225	332
		Lower NF Nooksack 1711000402		239,902	315	304,217	400
		MF Nooksack 1711000403		73,439	285	93,419	363
		SF Nooksack 1711000404		221,835	462	235,548	490
			Nooksack – Frontal Bellingham Bay 1711000405	1,181,563	545	1,234,109	570

Table E-7. An overview of shallow (<30m) groundwater nitrate concentrations and associated land-based loading.

Drainage Name	Area (km^2)	Sample No.	Groundwater Nitrate Concentration (mg/L)			Land-Based Annual Yield (kg/yr)
			65th Percentile	75th Percentile	25th Percentile	
Lower NF Nooksack	261	17	0.80	0.83	0.65	528
Nooksack – Frontal Bellingham	668	586	5.22	7.95	0.32	900
Sumas	150	95	5.42	9.44	0.79	1,446

Crab Creek

The Crab Creek HUCs and their position in the overall watershed flow network are provided in Figures E-4 and E-5. (The flow network conforms to natural drainage as opposed to irrigation influences.) The Crab Creek watershed is located in central Washington and is relatively flat and arid, though through irrigation it is among the most intensively managed areas for agricultural crop production in the state. Irrigation within the Crab Creek basin is associated with the massive Columbia Basin Project which starts with water diversion from the Columbia River at the Grand Coulee Dam. Water is imported to the basin and many of the natural stream channels are used to convey irrigation flows with depression areas within the watershed often serving as storage.

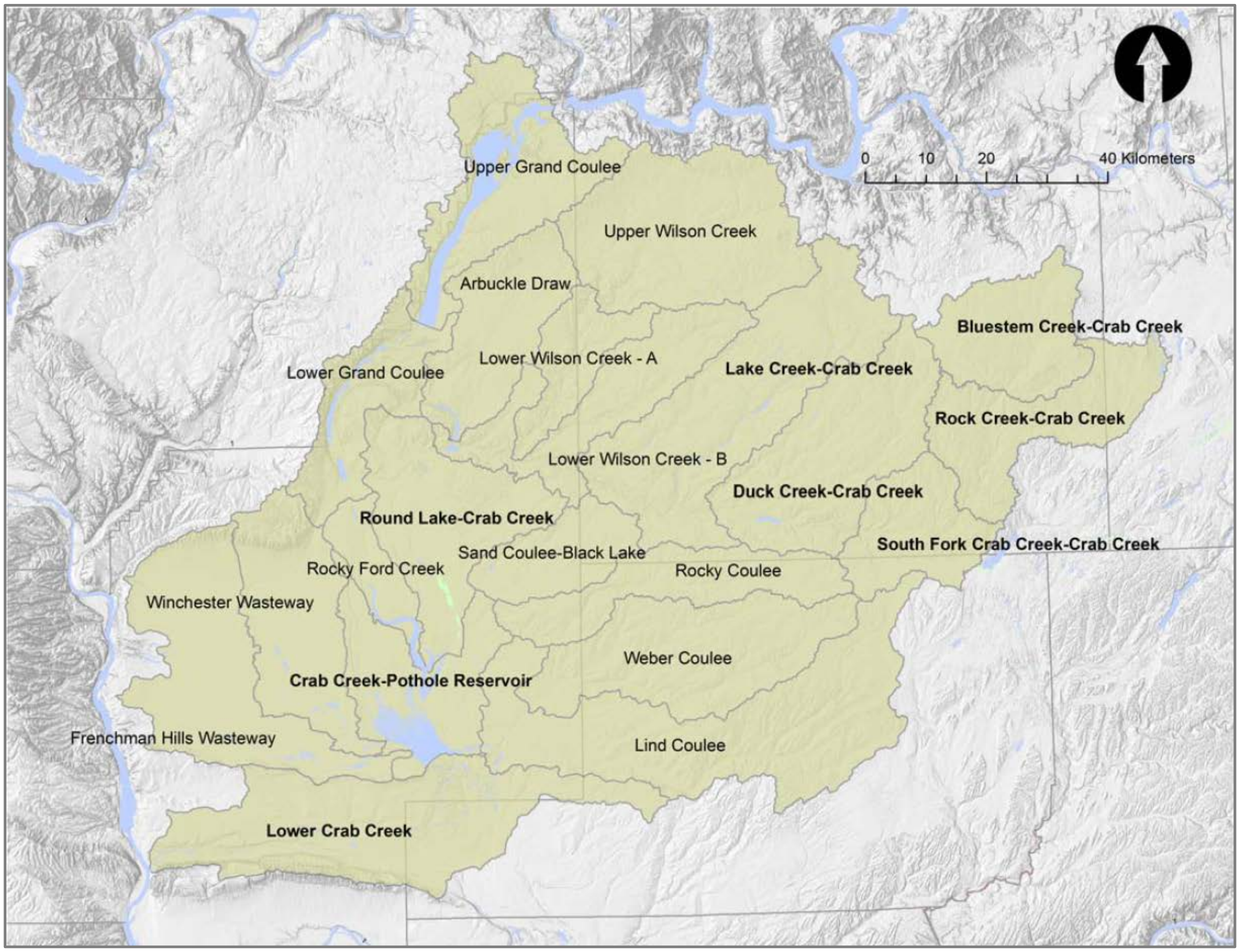

Figure E-4. The Crab Creek watershed and associated HUCs.

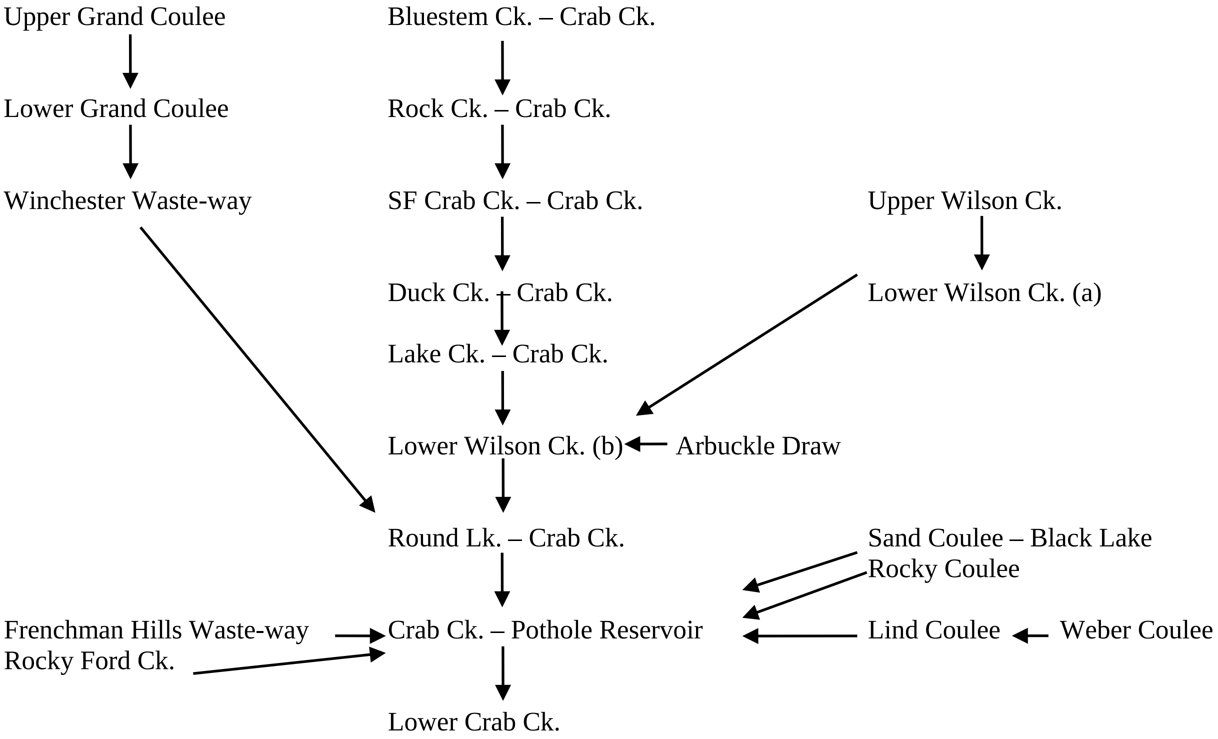

Figure E-5. Flow Schematic for Crab Creek based on USGS HUC-10 delineation.

Overview of land use

Land use in the Crab Creek watershed has an east/west division with the defining element access to irrigation. The Columbia Basin Project was originally intended to provide irrigation to majority of the watershed, but has remained largely confined to the western portion since its inception. HUCs with access to irrigation include: Lower Crab, Frenchman, Winchester Waste-way, and Potholes Reservoir in addition to the most western sections of Lind and Weber Coulees, and Round Lake (Figure E-4). In total about 2,700 km^2 receive irrigation within the greater Project area (which extends beyond the Crab Creek watershed) at an annual rate of 3.1 km^3. This equates to an average application rate of 1.1 meters of water per square meter of land, comparable to the annual rainfall levels of western Washington. Because Crab Creek watershed is situated in the driest region of Washington, with an average annual rainfall of 0.18 m/yr, land outside of the irrigation scheme is primarily in dry-land wheat production unless groundwater is accessed as a water source. The land use division created by access to irrigation can be observed in the representation of land uses.

Referring to Table E-8, irrigated land includes HUCs with a high level of pasture/hay production such as Crab-Potholes (pasture/hay production encompasses 18% of HUC area), Frenchman (26%), Lower Crab (22%), and Winchester Waste-way (18%). In comparison, HUCs situated outside of the irrigation scheme such as Arbuckle Draw, Bluestem, Duck Creek, Upper and Lower Wilson, Rock Creek, Rocky Coulee, and South Fork Crab all have hay/pasture production representing less than 3% of the land area (Table E-8). Instead, small grain (wheat) production is observed at a median level of 60% of the land area for these HUCs. HUCs with partial access to irrigation including Lind, Sand, and Weber Coulees have hay/pasture production in their western irrigated portion and dry-land wheat production in their eastern half. The median level of hay and dry land wheat production for these HUCs is 8% and 60%, respectively indicating the majority of the land is situated beyond the irrigation network. Another land use situated solely in the irrigated portion of the watershed are row crops encompassing about 11% of the Lower Crab HUC, 4% of Frenchman, and 3% of the Winchester Waste-way HUC. A distinguishing feature of the Crab Creek watershed are areas where there is surface exposure of basalt and soils are either too thin to non-existent to allow crop production. This landscape is most prevalent in the Lower Grand Coulee and Lake Creek HUCs and is distinguished in the NLCD descriptions by the shrub-land description, which tends to be associated with non-arable land. These HUCs come as close as a background nitrate loading condition can be described for this watershed.

Higher representation levels of open water present for Crab-Potholes and Upper Grand Coulee are associated with the Columbia Basin Project irrigation scheme. The 109 km^2 Banks Lake that forms the headwaters of the irrigation scheme is situated in the Upper Grand Coulee HUC and the Potholes Reservoir is situated in the Crab-Pothole HUC. Crab Creek flows into Moses Lake at the city of Moses Lake prior to its discharge to the Potholes Reservoir situated just south of the lake.

Table E-8. The percent representation of NLCD land uses within the Crab Creek watershed, by HUC.

HUC Name HUC No.	Open Water	Urban	Bare Rock	Forest & Shrub-land	Deciduous Cover	Pasture	Grass-land	Orchard	Small Grain	Row Crop
Arbuckle Draw 1702001403	1.1	0.6	===	34.9	===	2.3	1.9	===	59.3	===
Bluestem 1702001301	0.2	1.0	===	16.5	0.1	0.2	1.9	===	79.9	===
Crab-Pothole 1702001509	19.1	4.4	===	30.4	===	18.0	7.6	===	16.9	0.2
Duck Creek 1702001304	0.4	1.2	===	32.0	===	2.4	2.8	===	60.8	===
Frenchman 1702001506	0.9	2.5	===	28.0	===	25.8	4.9	1.4	31.6	4.2
Lake Creek 1702001305	1.1	0.8	===	69.5	0.1	1.3	4.2	===	22.2	===
Lind Coulee 1702001508	0.3	2.1	===	26.9	===	8.0	2.1	===	60.5	===
Lower Crab 1702001510	1.6	1.4	0.1	47.6	===	22.3	7.1	===	8.8	10.6
Lower Grand Coulee 1702001402	4.3	2.9	===	73.6	0.1	2.1	5.3	1.5	10.0	===
Lower Wilson (a) 1702001307	===	0.6	===	42.4	0.1	1.6	3.2	===	52.2	===
Lower Wilson (b) 1702001308	1.0	0.9	===	49.3	0.1	2.7	4.4	===	41.5	===
Rock Creek 1702001302	0.7	1.4	===	40.7	0.1	1.3	2.6	===	52.4	===
Rocky Ford 1702001503	8.9	3.6	0.1	42.2	0.1	3.5	39.1	2.0	0.5	===
Rocky Coulee 1702001502	===	0.6	===	24.4	===	2.0	4.2	===	68.9	===
Round Lake 1702001504	0.9	3.8	===	56.3	===	14.6	9.4	0.1	14.0	===
Sand Coulee 1702001501	0.1	0.8	===	41.4	===	10.7	5.0	===	42.0	===
South Fork Crab 1702001303	0.1	1.0	===	39.3	0.1	1.3	4.3	===	53.9	===
Upper Grand Coulee 1702001401	16.3	0.7	===	43.3	===	===	5.2	===	34.5	===
Upper Wilson 1702001306	0.2	0.9	===	22.3	===	===	3.3	===	73.2	===
Weber Coulee 1702001507	0.1	2.0	===	28.4	===	6.3	3.3	===	60.0	===
Winchester Waste-way 1702001505	1.2	2.8	0.1	36.6	===	17.9	7.5	2.2	26.5	3.0

Population centers within the watershed include Moses Lake (situated in the Rocky Ford, Crab-Pothole, Round Lake HUCs), Ephrata (Rock Ford, Winchester Waste-way), Ritzville (Lind Coulee), Quincy (Frenchman Hills Waste-way), Royal City (Lower Crab), and Othello (Lower Crab). These and other smaller dispersed towns throughout the non-irrigated wheat land tend to have municipal wastewater treatment with the majority of the discharge land applied (Table E-9). Dairy production is present at a relatively low level primarily within the irrigated section of the watershed and dispersed.

Table E-9. Nitrate loading attributes for the Crab Creek watershed: human, dairy and beef cattle populations, and municipal wastewater discharge levels to surface water and land surface.

HUC Name	Population (No.)	Municipal Surface Discharge (m^3/yr)	Municipal Land Discharge (m^3/yr)	Dairy Cows (No.)	Beef Cows (No.)
Arbuckle Draw	312	===	===	===	9,643
Bluestem	1,253	111,463	===	===	1,539
Crab-Pothole	14,984	===	2,952,020	724	9,756
Duck Creek	782	===	227,712	196	2,675
Frenchman	10,170	===	1,480,463	3,618	15,579
Lake Creek	1,542	96,316	===	===	3,560
Lind Coulee	4,664	86,246	544,310	3,618	11,035
Lower Crab	11,547	1,452,092	212,717	5,343	16,758
Lower Grand Coulee	4,506	===	408,673	===	6,788
Lower Wilson (a)	236	===	===	===	3,313
Lower Wilson (b)	524	===	===	===	5,330
Rock Creek	2,181	===	===	===	2,049
Rocky Ford	6,281	===	===	===	3,525
Rocky Coulee	328	===	===	1,224	4,033
Round Lake	19,992	===	453,744	4,342	12,950
Sand Coulee	323	===	===	===	4,095
South Fork Crab	304	===	===	===	1,654
Upper Grand Coulee	2,271	===	===	===	9,035
Upper Wilson	1,733	246,179	104,453	===	3,390
Weber Coulee	674	===	===	===	6,187
Winchester Waste-way	7,752	===	868,760	2,894	11,490
Watershed	**92,358**	**1,992,295**	**7,252,853**	**21,959**	**144,385**

Results

Loading to land surface / groundwater

Tables E-10 and E-11 provide the net annual land-based nitrate load by source and its relative level of representation for each of the Crab Creek HUCs. Overall, considering the entire watershed, small grain production (wheat) provides the single greatest source of nitrate at about 53% of the annual load total. The level of representation among the other sources is significantly lower with beef cattle (12%), shrub-land, which is considered a background-type source (8%), municipal wastewater, dairy production (7% each) and pasture/hay production (6%), having the next highest levels. For the HUCs with the greatest nitrate yields, Winchester Waste-way and Frenchman Hills, wheat comprised only about 25% of the annual load, with greater loading associated with municipal wastewater infiltration.

Table E-10. Estimated net annual nitrate load (kg) applied to the land surface within each of the Crab Creek HUCs

HUC Name	Urban	Forest & Shrub-land	Land-Based Municipal Discharge	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain	Row Crops
Arbuckle Draw	92	3,635	===	84	===	10,414	896	466	===	38,233	===
Bluestem	134	1,541	===	120	===	1,662	82	425	===	46,106	===
Crab-Pothole	662	3,218	1,461	===	3,057	10,537	7,269	1,904	===	11,093	352
Duck Creek	278	5,107	4,554	===	828	2,889	1,443	1,080	===	60,117	===
Frenchman	599	4,730	29,609	===	15,286	16,825	16,555	1,969	2,608	33,008	9,456
Lake Creek	254	14,857	===	228	===	3,845	1,085	2,134	===	29,430	===
Lind Coulee	743	6,569	10,886	25	15,286	11,918	7,433	1,193	===	91,542	===
Lower Crab	441	10,373	4,254	===	22,574	18,099	18,509	3,702	===	11,906	30,845
Lower Grand Coulee	365	6,381	8,174	417	===	7,331	706	1,092	1,489	5,361	===
Lower Wilson (a)	43	2,323	===	64	===	3,578	332	412	===	17,709	===
Lower Wilson (b)	147	5,490	===	141	===	5,757	1,126	1,166	===	28,598	===
Rock Creek	233	4,600	===	589	===	2,213	570	706	===	36,716	===
Rocky Ford	196	1,611	===	1,696	===	3,807	504	3,547	893	116	===
Rocky Coulee	80	2,311	===	88	5,173	4,356	707	938	===	40,351	===
Round Lake	740	7,735	9,075	4,510	18,343	13,986	7,614	3,089	161	11,898	===
Sand Coulee	71	2,572	===	87	===	4,422	2,534	736	===	16,165	===
South Fork Crab	116	3,134	===	82	===	1,786	394	809	===	26,591	===
Upper Grand Coulee	139	6,233	===	613	===	9,758	===	1,766	===	30,746	===
Upper Wilson	239	4,119	2,089	===	===	3,661	30	1,454	===	83,513	===
Weber Coulee	443	4,466	===	182	===	6,682	3,745	1,244	===	58,378	===
Winchester Wasteway	492	4,498	17,375	393	12,229	12,409	8,384	2,195	3,045	20,160	4,858
Watershed	**6,508**	**105,61**	**87,478**	**9,321**	**92,777**	**155,93**	**79,919**	**32,025**	**8,196**	**697,73**	**45,511**

The lowest net land surface nitrate loading yields were estimated to occur within the Lake Creek (51 kg/km^2-yr), Rocky Ford (75 kg/km^2-yr), and Lower Grand Coulee (79 kg/km^2-yr) HUCs (Figure E-6). Due to the intensity of the land use in the watershed, these yields are still 2 to 4 times greater than what is estimated to represent a background loading condition. In common with these HUCs is that they have a relatively high representation of shrub and (or) grassland compared to the other HUCs. The highest nitrate loading yields occur within the irrigated portions of the watershed for HUCs Round Lake (120 kg/km^2-yr), Rocky Coulee (120 kg/km^2-yr), Lind Coulee (126 kg/km^2-yr), Winchester Waste-way (149 kg/km^2-yr), and Frenchman Hills Waste-way (164 kg/km^2-yr). The loading yields are estimated at between 6 to 8 times greater than background. For Frenchman, like many of the other HUCs with high loading yields, there is not a single dominant nitrate source instead it comes from the combination of several sources. Wheat production provides the greatest source at 25% of the annual yield, followed by municipal wastewater (23%), dairy, beef, and hay/pasture (all 12-13%), and row crops (7%). The Winchester Hills Waste-way, the HUC with next highest annual nitrate yield, had similar types of nitrate sources and their levels of representation.

The Crab Creek watershed is heavily managed for agricultural production and even the yields estimated for the Rocky Ford HUC, among the lowest determined within the watershed, are still among the highest yields estimated considering the eastern Washington study locations and Yakima HUCs (refer to Figure 19). The overall watershed land-based nitrate yield is 103 kg/km^2-yr. As a consequence, the shallow groundwater nitrate concentrations tend to be uniformly high (Table E-12, Figure 19). Based on the relationship between the land-based nitrate yield and associated shallow groundwater concentration, a 65th percentile concentrations for the watershed of 4.5 mg/L can be expected. In particular, Lower Crab, Winchester Waste-way, and Frenchman Hills HUCs all had 65th percentile shallow groundwater nitrate levels of about 7 mg/L, indicating excessive source loading. The representation of source loads for Lower Crab differ from Winchester and Frenchman in that row crops represents a greater percent of the overall load (26%) followed by dairy production (18%).

Table E-11. Percent representation of the net annual load by land use for the Crab Creek HUCs.

HUC Name	Urban	Forest & Shrub-land	Land-Based Municipal Discharge	On-Site Wastewater	Dairy	Beef	Pasture	Grass-land	Orchard	Small Grain	Row Crops
Arbuckle Draw	0.2	6.8	===	0.2	===	19.3	1.7	0.9	===	71.0	===
Bluestem	0.3	3.1	===	0.2	===	3.3	0.2	0.8	===	92.1	===
Crab-Pothole	1.7	8.1	3.7	===	7.7	26.6	18.4	4.8	===	28.0	0.9
Duck Creek	0.4	6.7	6.0	===	1.1	3.8	1.9	1.4	===	78.8	===
Frenchman	0.5	3.6	22.7	===	11.7	12.9	12.7	1.5	2.0	25.3	7.2
Lake Creek	0.5	28.7	===	0.4	===	7.4	2.1	4.1	===	56.8	===
Lind Coulee	0.5	4.5	7.5	===	10.5	8.2	5.1	0.8	===	62.9	===
Lower Crab	0.4	8.6	3.5	===	18.7	15.0	15.3	3.1	===	9.9	25.6
Lower Grand	1.2	20.4	26.1	1.3	===	23.4	2.3	3.5	4.8	17.1	===
Lower Wilson (a)	0.2	9.5	===	0.3	===	14.6	1.4	1.7	===	72.4	===
Lower Wilson (b)	0.3	12.9	===	0.3	===	13.6	2.7	2.7	===	67.4	===
Rock Creek	0.5	10.1	===	1.3	===	4.8	1.2	1.5	===	80.4	===
Rocky Ford	1.6	13.0	===	13.7	===	30.8	4.1	28.7	7.2	0.9	===
Rocky Coulee	0.1	4.3	===	0.2	9.6	8.1	1.3	1.7	===	74.7	===
Round Lake	1.0	10.0	11.8	5.8	23.8	18.1	9.9	4.0	0.2	15.4	===
Sand Coulee	0.3	9.7	===	0.3	===	16.6	9.5	2.8	===	60.8	===
South Fork Crab	0.4	9.5	===	0.2	===	5.4	1.2	2.5	===	80.8	===
Upper Grand	0.3	12.7	===	1.2	===	19.8	===	3.6	===	62.4	===
Upper Wilson	0.3	4.3	2.2	===	===	3.8	===	1.5	===	87.8	===
Weber Coulee	0.6	5.9	===	0.2	===	8.9	5.0	1.7	===	77.7	===
Winchester Waste-	0.6	5.2	20.2	0.5	14.2	14.4	9.7	2.6	3.5	23.4	5.6
Watershed	**0.5**	**8.0**	**6.6**	**0.7**	**7.0**	**11.8**	**6.0**	**2.4**	**0.6**	**52.8**	**3.4**

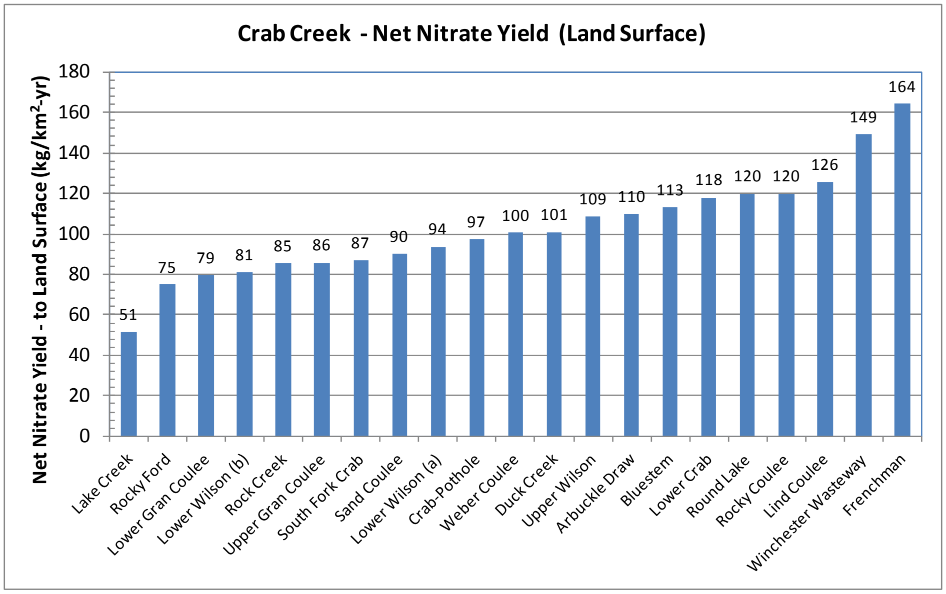

Figure E-6. Net land-based nitrate yields, by HUC, estimated for the Crab Creek HUCs.

Table F-12. An overview of shallow (<30m) groundwater nitrate concentrations and associated land-based loading.

Drainage Name	Area (km^2)	Sample No.	Groundwater Nitrate Concentration (mg/L)			Land-Based Annual yield kg/km^2-yr
			65th Percentile	75th Percentile	25th Percentile	
Crab-Pothole	504	38	5.49	7.87	1.83	97
Frenchman Hills	803	52	7.30	7.99	3.34	164
Lower Crab	1,039	38	6.98	8.19	1.65	118
Round Lake	654	20	5.37	6.03	2.29	120
Winchester Waste-way	585	26	7.18	8.49	2.34	149

Loading to surface water

About 23% of the Crab Creek watershed receives irrigation at an approximate level of 1 m^3/m^2-yr. The other 77% of the watershed is situated outside of the Columbia Basin Project irrigation scheme and receives an average of 0.19 m^3/m^2-yr from precipitation. Despite the contribution to flow associated with irrigation, the high level of exposed storage (lake, reservoir, open canals) and the intersection between the irrigation season and peak annual evaporation rates, crop uptake and transpiration, the runoff yield for the Crab Creek watershed remains low at 0.016 m^3/m^2-yr, the lowest of the study watersheds. This results in concentrating the nitrate loading in both surface and groundwater leading to the high observed concentrations. In terms of surface water export of nitrate, offsetting the flow-concentrating factor, are the series of lakes and reservoirs along Crab Creek's complex flow path. All serve to significantly reduce the total amount of nitrate exported through various attenuation processes. As discussed previously, on a watershed basis there is about a 77% loss of the total net annual nitrate load in Crab Creek due primarily to attenuation occurring in the series of lakes and reservoirs situated along the creek's flow-path.

In assessing the net level of nitrate export from the Crab Creek watershed in surface flow it is assumed that sources situated within HUCs that ultimately drain to the Potholes Reservoir, a central and lower watershed situated reservoir, have an insignificant bearing on the level ultimately exported. (This is not altogether correct in that the Winchester and Frenchman Hills waste-ways both collect irrigation return flows and direct them to the Potholes Reservoir. Given these concentrated flows it is expected that nitrate concentrations in flow leaving the Potholes Reservoir, while greatly reduced, likely remain elevated.) The exception are sources situated in Lind and Weber Coulees which while also discharging to the Potholes Reservoir do so in proximity to the reservoir's outlet, short-circuiting potential loss pathways (Figure F-4).

Table E-13. Estimated net annual nitrate loading to surface water and land surface for the Crab Creek HUCs.

		Net Nitrate Load and Yield to Land Surface		Net Nitrate Load and Yield to Surface Water	
HUC Name	Drainage Area (km^2)	Net Load kg/yr	Net Yield kg/km^2-yr	Net Load kg/yr	Net Yield kg/km^2-yr
Arbuckle Draw	496	53,823	110	48,508	98
Bluestem	444	50,076	113	51,488	116
Crab-Pothole	504	39,588	97	===	===
Duck Creek	760	76,307	101	73,216	96
Frenchman	803	130,650	164	123,794	154
Lake Creek	1018	51,858	51	42,765	42
Lind Coulee	1163	145,599	126	143,682	124
Lower Crab	1039	120,715	118	133,541	129
Lower Grand Coulee	413	31,390	79	13,785	33
Lower Wilson (a)	261	24,468	94	24,397	93
Lower Wilson (b)	530	42,436	81	37,156	70
Rock Creek	539	45,648	85	41,645	77
Rocky Ford	182	12,373	75	===	===
Rocky Coulee	451	54,006	120	53,971	120
Round Lake	654	77,559	120	71,406	109
Sand Coulee	296	26,588	90	26,281	89
South Fork Crab	380	32,917	87	32,499	86
Upper Grand Coulee	686	49,263	86	===	===
Upper Wilson	878	95,115	109	98,702	112
Weber Coulee	749	75,141	100	74,686	100
Winchester Waste-way	585	86,048	149	78,785	135
Watershed	**12,830**	**1,321,570**	**103**	**1,170,308**	**91**

This assumption and its application provide a close estimate between the observed net annual load (Crab Creek @Beverly monitoring location) and that estimated by the export methods. The total annual net load estimated for Lind and Weber Coulees and the Lower Crab is 351,909 kg/yr compared to the observed level of 385,279 kg/yr. Based on this assumption, only sources situated within the lower 23% of the drainage area contribute to export from the watershed, while nitrate associated with the other 77% is largely captured within the various lakes and reservoirs.

Considering the entire drainage area, there is a net nitrate yield of about 27 kg/km^2-yr, an exceptionally low level, not far from an expected background level, the result of storage losses. However, the net nitrate yield is 118 kg/km^2-yr considering just the area encompassing lower Crab Creek, Lind and Weber Coulee; a level more in-line with the observed nitrate concentrations.